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REMOVAL OF OUT-OF-PLANE DISTORTION IN MILD STEEL PANELS USING FLAME HEATING

by

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Submitted to the Department of Ocean Engineering on May 8, 1987 in partial fulfillment of the requirements for the degree of S.M., Naval Architecture and Marine Engineering.

ABSTRACT

The nature of distortion, the effects of welding, methods of removing distortion, and previous investigations on removing distortion in welded metal structures were discussed. A procedure for linear flame straightening panel structures, used aboard U.S. Naval ships, and the selection of parameters was then presented. The only variable during line heating was the heating flame velocity. "T" shaped unrestrained mild steel specimen, 1/8" and 3/16" thick, were fillet welded and then line heated to provide an angular distortion vs velocity relationship. Two panel structures (one using 1/8" plate, the other using 3/16" plate) similar to ship deck plates were fabricated and then line heated using the method and relationship determined from the "T" shaped specimen.

The results of testing were presented in the form of distortion tables and graphs. It was found that line heating along the back side of fillet welded stiffeners was an effective way of removing out-of-plane and angular distortion. If the flame velocity was too low while flame straightening one panel, then the adjacent panels were also affected. Also, line heating parallel to the stiffeners did not remove buckling distortion.

This study represents a first step in the investigation of flame straightening multi-panelled metal structures. Recommendations for additional testing using a combination of flame heating types, to remove all forms of panel structure distortions were presented.

Thesis Supervisor: Professor Koichi Masubuchi

Title: Professor of Ocean Engineering and Materials Science

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CHAPTER ONE

INTRODUCTION

1.1 General Remarks

Shrinkage of weld metal and the accompanying residual stresses and distortion is a perennial problem in the shipbuilding industry. Much effort has been expended to minimize the distortion that occurs during ship construction. While distortion can be produced by many of the assembly procedures used in ship fabrication, its principal cause today is welding. Welding is used extensively in modern shipbuilding yards, since it offers many advantages (i.e. high joint efficiency, water and air tightness, weight saving, no limit on thickness, simple structural design, and reduction in fabrication time and cost [1]) over other assembly methods such as riveting, casting, and forging.

Many ideas have been advanced as solutions to the problem of distortion. Unfortunately, these ideas and theories are often in conflict. Although welding has been used extensively in ship construction since the 1930's, there is very little published experimental or theoretical work on the control and removal of distortion.

1.2 Nature of Distortion

Distortion in weldments is primarily the result of the combined effects of (1) locally-applied heat in the weld zone, and (2) restraint provided by both the relatively cold metal on either side of the weld bead and by other members of the

structure [2]. Because a weldment is heated locally by the welding heat source, the temperature and stress distribution in the weldment is not uniform and changes as welding progresses (Figure 1-1). During the heating and cooling cycle of the welding process, complex strains occur in the solidified weld metal and base metal regions near the weld. The strains produced during heating may be accompanied by plastic upsetting.

For example, when a plate is heated along a line, such as with a torch, it will bend upon cooling so as to form a slight knuckle along the line. The curvature achieved is the same as if the plate were worked slightly with a press except that some shrinkage occurs; see Figure 1-2. Such heating can be applied in all directions many times over, or between and/or on bends formed by previous heating. What actually happens is illustrated in Figure 1-3. Local heating creates thermal stress in a very small region. Young's Modulus and the Elastic Limit of the effected material both decrease with the rise in temperature [3,4]. As the heat source travels, the adjacent material even if not cooled with water remains cool enough to resist the thermal created stress. So constrained, the heated surface swells beyond its Elastic Limit and therefore after cooling retains some minute deformation. During the cooling process, the bulge-side surface contracts more than the other side resulting in angular distortion (bending) and some amount of overall shrinkage.

See Appendix B for a discussion of the "Fundamentals of

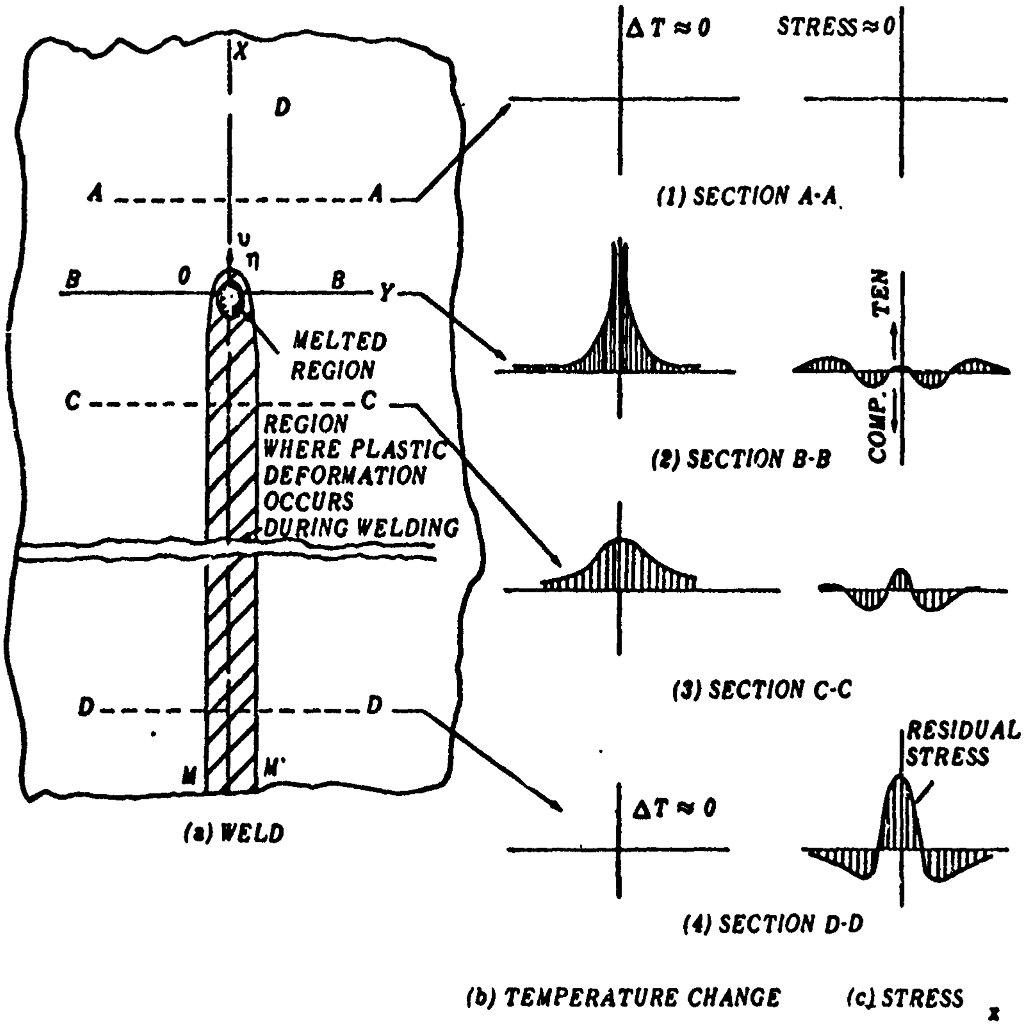


Figure 1-1: SCHEMATIC REPRESENTATION OF CHANGES OF TEMPERATURE AND STRESSES DURING WELDING.

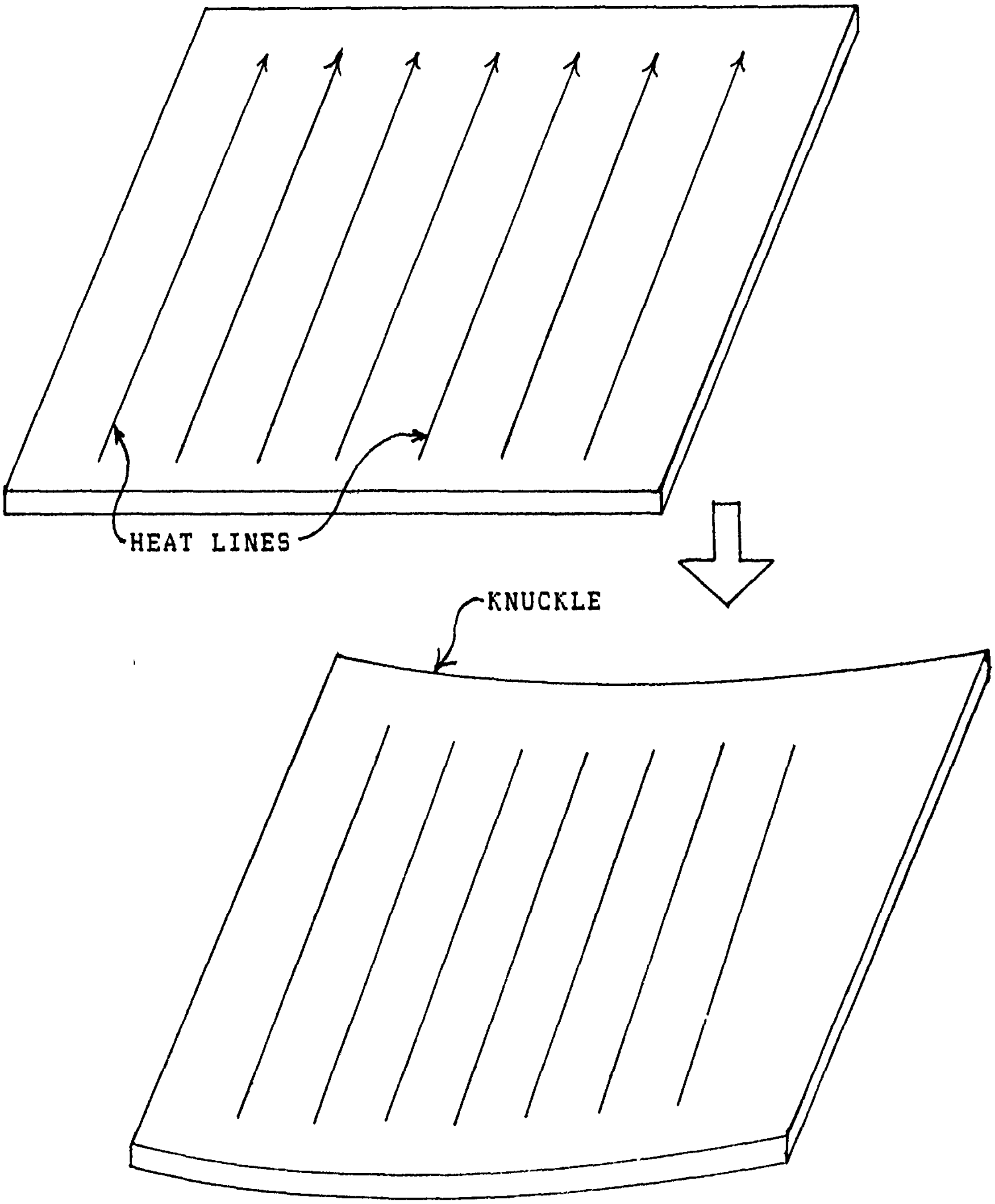


Figure 1-2: CURVATURE ACHIEVED BY LINE HEATING

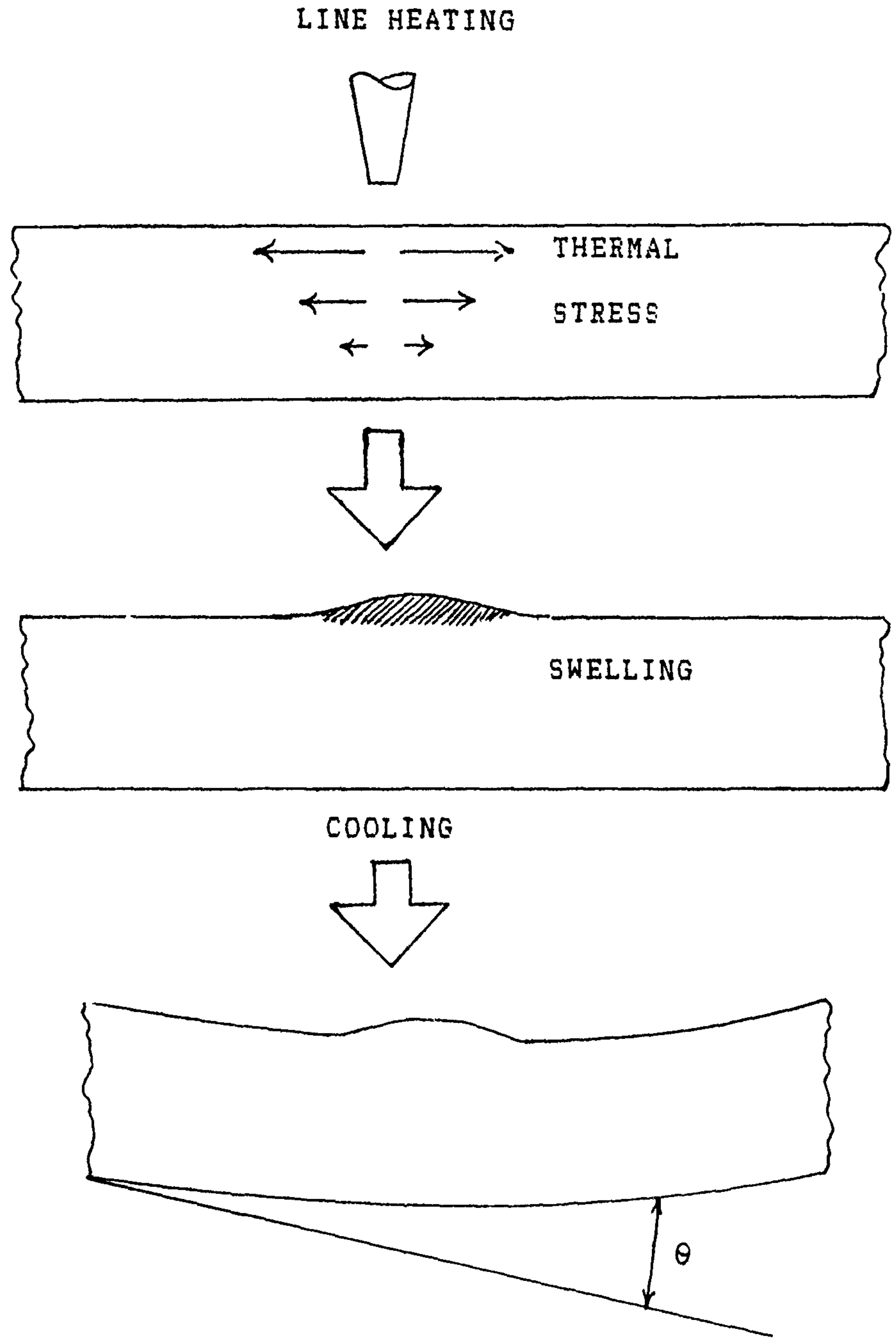


Figure 1-3: LOCAL HEATING CREATES THERMAL STRESS IN A VERY SMALL REGION. TORCH TRAVEL IS IN THE DIRECTION TOWARD THE READER.

Line Heating".

1.3 Distortion in Welded Structures

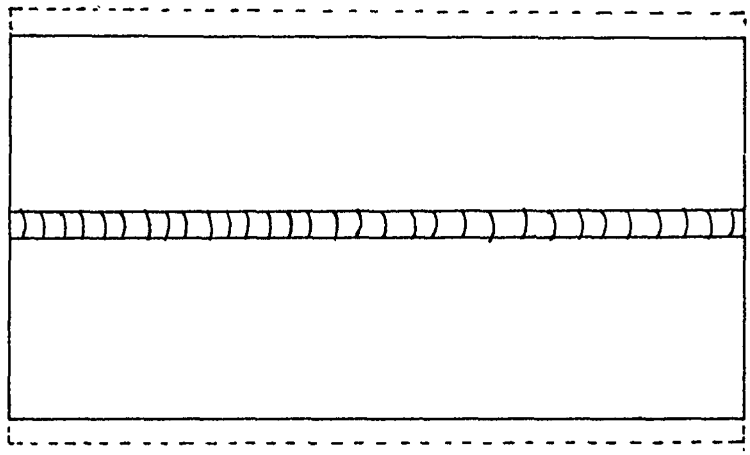
Residual stresses and the resulting distortion in structural weldments are caused by three fundamental dimensional changes [1]:

1. Transverse shrinkage perpendicular to the weld line,
2. Longitudinal shrinkage parallel to the weld line, and
3. Angular distortion (rotation around the weld line).

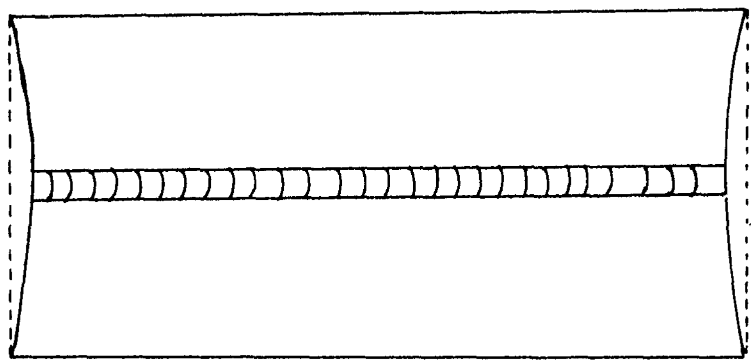
The effects of these dimensional changes on butt and fillet welds are shown in Figure 1-4. These three dimensional changes are always combined in shipbuilding and the analysis of distortion is extremely complex. Yet, to date, most analytic solutions to distortion problems involve simple structures.

Longitudinal and transverse shrinkage are essentially designed out of ship structures. If proper shrinkage allowances were not allocated during piece fabrication, the final assembly would not fit together. However, angular changes, particularly in the area of fillet welds, are a problem.

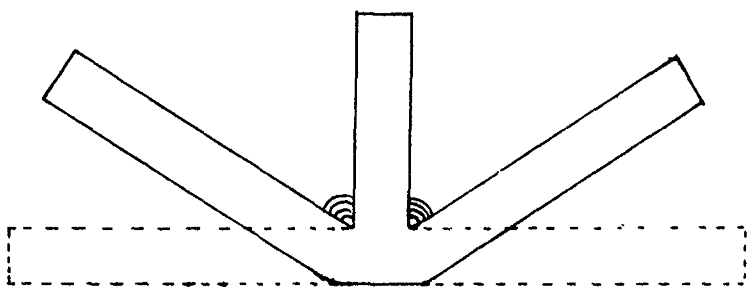
While angular distortion can be minimized and/or controlled by proper design of the weldment and careful selection of the welding process and welding variables, some inevitably occurs. When the amount of angular distortion



(a) TRANSVERSE SHRINKAGE



(b) LONGITUDINAL SHRINKAGE



(c) ANGULAR DISTORTION

Figure 1-4: FUNDAMENTAL TYPES OF DIMENSIONAL CHANGES DUE TO WELDING

exceeds acceptable limits, it must be removed.

1.4 Methods of Removing Angular Distortion

Angular distortion has been removed in the past by the following methods [1,2,3,4,5,6,7,8]:

1. Mechanical pressing of members which are small enough to be handled by a press.
2. Jacking of members in place. Usually this method requires the welding of a strongback in place to transmit the jacking force. Jacking can be accomplished with or without the application of heat.
3. Hammering of locally heated areas.
4. Peening of the weld metal itself.
5. Cutting the distorted panel, thus removing some material and welding the cut back together.
6. Applying weld beads to the concaved side of the panel to cause shrinkage stresses and draw the panel straight.
7. Flame heating of members in place with the use of the oxyacetylene flame alone or combined with a water quench.
8. Vibratory stress relieving. A variable speed vibrator is clamped to the weldment and vibrated at resonant frequency for 10 to 30 minutes to remove distortion.

The primary method used in shipyards for removing angular distortion in ordinary carbon steels is flame heating. It is

used because it is both an economical and easy method to employ compared to all other available methods.

Only limited scientific information, either analytical or experimental, is available on mechanisms of distortion removal using flame heating. Thus flame straightening is very much an art. Usually, to remove distortion, the senior welder determines where a distorted plate should be heated. If the first application of heat fails, a second "guess" is made and heat again applied. This process is continued until the distortion is removed or reduced to acceptable limits.

The flame straightening methods used to remove angular distortion are [1,2,3,4,5,6,7,8]:

1. Spot Heating. In spot heating, heat is applied at a number of spots on the plate, as shown in Figure 1-5a. Spot heating is used to remove distortion in thin plated structures.
2. Line Heating of the panel. In this procedure, shown in Figure 1-5b, the area to be straightened is heated along narrow lines within the panel.
3. Line Heating of the back side of fillet welds. This procedure, shown in Figure 1-5c, is similar to 2 above except the flame is applied to the back side of the welded plate.
4. Line Heating approximately three to four inches away from the fillet weld along a single line. This method, shown in figure 1-5d, was developed in a German shipyard.

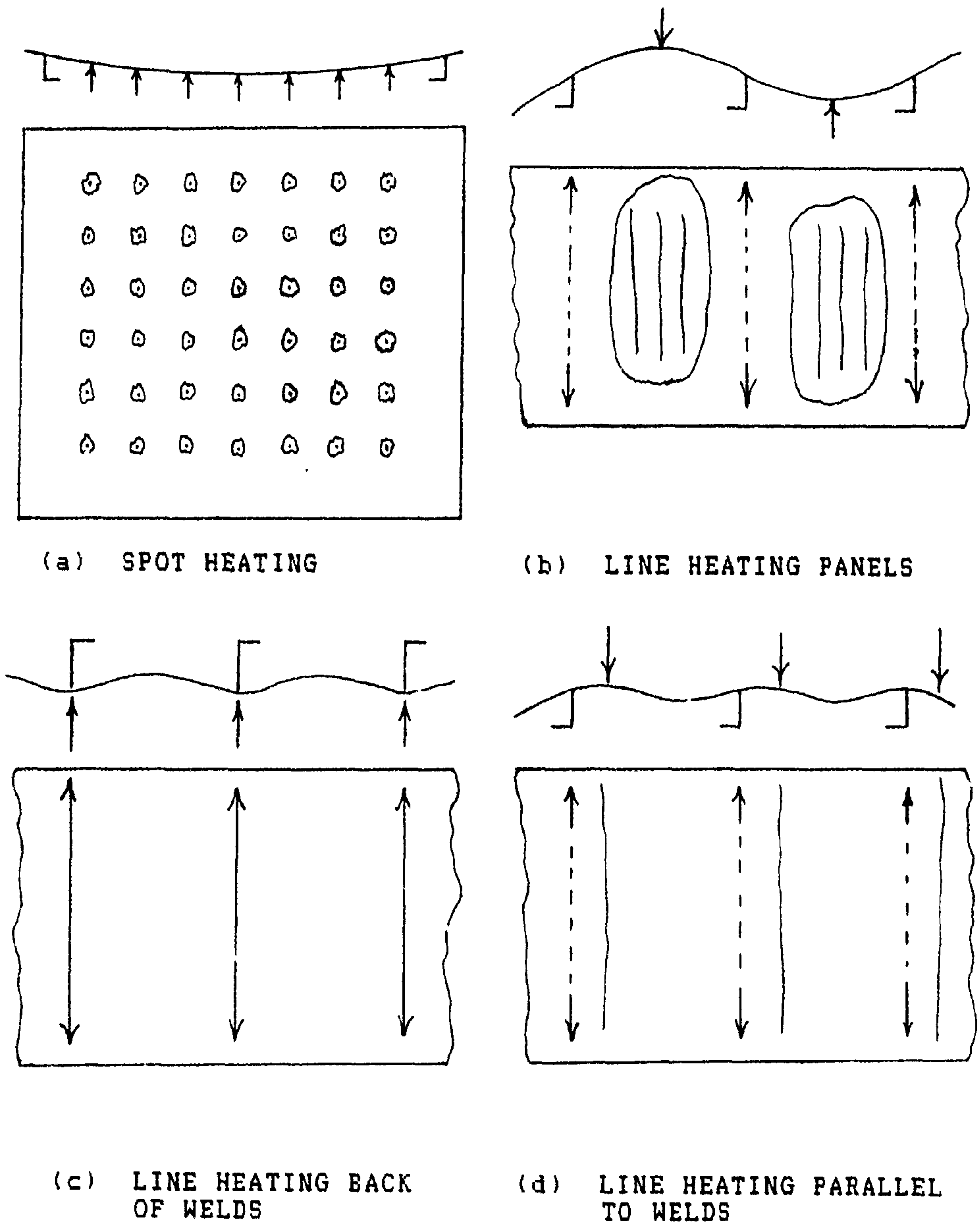


Figure 1-5: FLAME STRAIGHTENING METHODS

1.5 Previous Investigations

A search of the literature on flame straightening theory and shrinkage distortion produced limited results concerning previous experimental investigations or analyses. This was particularly true for welded plates and structures. It must also be noted that all the research, both experimental and analytical, involved very simple welded structures, none more complicated than fillet welded panel structures.

Flame straightening theory relies on the same phenomena as welding, that is expansion and contraction of the material [3,9]. Steel expands or contracts in definite ratios to each degree of temperature change. The application of heat to the material must force the material to expand into itself in lieu of normal expansion in length. This means that colder surrounding material must produce the inward force on the heated zone [9]. Holt [3] showed that three basic facts must be known concerning a material to be flame straightened. These facts are:

1. Thermal expansion characteristics of material with a rise in temperature.
2. Variation of yield strength of material with rise in temperature.
3. Behavior of modulus of elasticity at elevated temperatures - i.e. the ratio of stress to strain.

He further explains that when an area is heated and then cooled, the material contracts in volume and exerts a pull that is equal to the yield point at the temperature of the

cooled volume. But angular distortion can be reduced, in materials less than 1/2 inch thick, by rapid line heating along the face to be concaved or shortened, using a single orifice oxyacetylene torch [4].

Flame heating investigations have been carried out at M.I.T.[10, 11, 12, 13, 14] and Battelle Memorial Institute [15]. Walsh [10], Duffy [11], and Johnson [12] performed a series of investigations to study deformation changes resulting from flame straightening techniques used on various welded plates and structures. Mild and higher strength steels of 3/8 inch and greater thicknesses were used. A summary of their conclusions are:

1. Spot flame straightening procedures are more effective on mild steel than on higher strength HY-80 steel [10].
2. Varying the position of spot flame straightening techniques from plate mid-span to fillet weld area produced no significant difference in reduced distortion [10].
3. When using line flame straightening techniques on panel structures, it is necessary to use a water quench to achieve distortion removal [11].
4. Line flame heating without water cooling is most effective for bending mild steel. The amount of bending depends on the material yield strength and variation of the yield strength with temperature. The direction of bending without the water cooling

is dependent on initial plate conditions and not the flame location. Thus, the direction of bending cannot be controlled by the heating [12].

5. Line flame heating when used for straightening should be applied parallel to the weld line, but on the opposite side and displaced slightly towards the center of the panel. Water cooling should be used to cause bending in the direction which will remove the distortion induced by the welding [12].

Battelle Memorial Institute [15] conducted experiments to determine the effects of flame heating and mechanical straightening on base metal properties. Figure 1-6, copied from the Battelle report, shows that above approximately 3/8 inch plate thickness, buckling type distortion does not occur. This figure also demonstrates that as plate thickness decreases the distortion problem increases.

1.6 Analytic Analysis of Weld Distortion

Because of the complex thermal, residual stress, elastic stress and strain, and plastic stress and strain fields produced by welding, to date only simple welded structures have been analytically analyzed by researchers [1, 4, 6, 7, 8, 16, 17, 18, 19, 20, 21, 22, 23, 24]. Shin [25] at M.I.T., developed a two dimensional analytical model using finite element methods that predicted, with reasonable degree of accuracy, the out-of-plane distortion readings experimentally obtained by Welsh [10] when line heating a simple panel structure. However, a search of literature did not provide

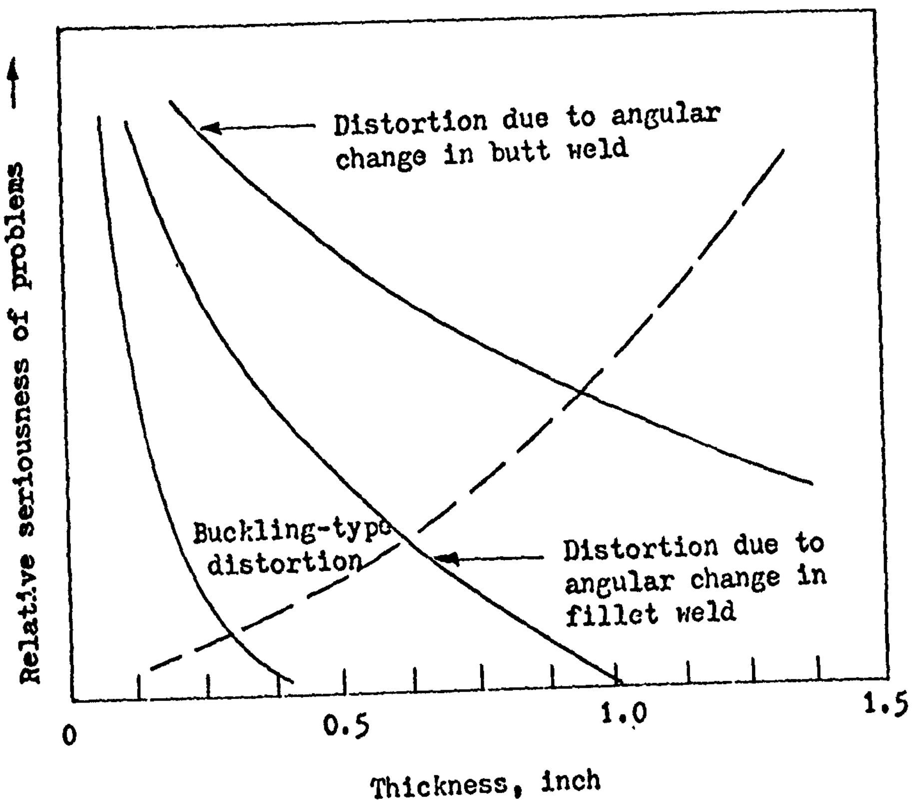


Figure 1-6: ILLUSTRATION OF THE EFFECTS OF PLATE THICKNESS ON THE RELATIVE SERIOUSNESS OF DISTORTION PROBLEMS AND MATERIAL PROBLEMS.

any models capable of predicting distortion in a complex welded structures, even one as simple and common as the one shown in Figure 1-7.

As higher strength, thinner plate steels are introduced into ship production, the need for predicting and removing unwanted welding distortion has increased.

1.7 Distortion Removal Using Robotics

Recent developments in robotic technologies, artificial intelligence, sensing technologies, and small, powerful computers may provide researchers with a means of predicting and removing distortion in complex welded structures.

An article by Imakita and Masubuchi [26] describes a procedure developed in a Japanese shipyard and currently under investigation at M.I.T. for measuring and removing out-of-plane distortion in panel structures. In summary, the paper discusses how a robot will be used to:

1. follow a predetermined path over the top of a welded panel, such as a ships deck, and measure the out-of-plane distortion,
2. analyze the measurement readings, by comparing it with data obtained previously, to determine what type of flame heating to apply in order to remove the distortion at each location,
3. pass over the panel again, this time applying flame heating of the appropriate type and velocity to remove some or all of the distortion measured on the first pass,

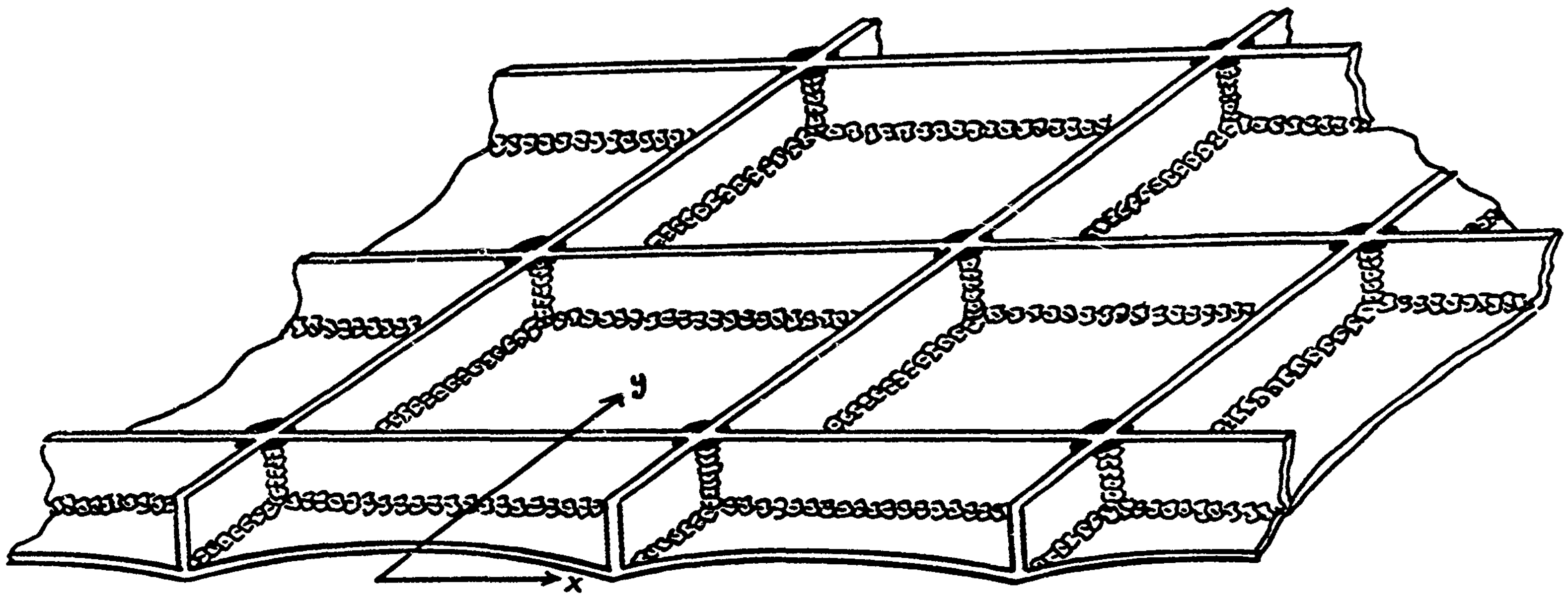


Figure 1-7: Panel Structure with Longitudinal and Transverse Stiffeners

4. repeat steps 1 through 3 until it is determined that all undesirable distortion is removed or that human assistance is required.

In order for step 2 of the procedure to be accomplished, data that the robot's computer can use must be experimentally obtained for each type of metal used. One of the purposes of this thesis is to accumulate data for thin mild steel panel structures. Once the robot is in operation the data base can be continuously updated and improved using data obtained from the most recent distortion removal job.

1.8 Purpose of this Study

Since there were no previous experimental investigations into flame straightening effects on multi-panel welded structures, this study represented the first step in that direction. The purpose of this study was:

1. To design and construct system models representing multiple panel plate and stiffener joints found in ship construction.
2. To observe the effects of using line flame heating to straighten mild steel panel structures containing fillet welded angular distortion.
3. Accumulate data on 1/8 inch and 3/16 inch thick mild steel panel structures. In the future, this data is to be used by robots in an "expert" system to remove panel distortion.
4. Compare distortion patterns obtained from multi-panel structures with those obtained from previous

experiments using single panel structures.

5. Observe the effect line heating one panel has on the other eight panels of the stiffened plate structures.

1.9 Parameter Selection

Mild steel was selected as the material to be investigated. It is still used extensively in ship construction, relatively inexpensive, and available. Plate and stiffener thicknesses of 1/8 inch and 3/16 inch were selected for this investigation. These plate thicknesses give large angular distortion for the size of panels used and the fabrication techniques employed in their construction.

There were 2 types of specimens used in this investigation. One was a flat square plate with a stiffener fillet welded across it's mid span (see Figures 2-1 and 2-2). This type of specimen will be referred to as a "free-end sample". The other type of specimen was a large plate with "T" shaped stiffeners welded to one side. The stiffeners were welded in a configuration that produced nine (9) panels as can be seen in Figure 2-7. This type of specimen will be referred to as a "stiffened plate". The stiffened plate configuration was selected based on plate and stiffener joint construction found on U.S. Naval Ship hulls. However, the dimensions were reduced in size for ease in construction and handling within the laboratory. The free-end samples were configured as those used in previous investigations at M.I.T.

All specimens were welded in the horizontal position

using the gas metal-arc (MIG), DCRP, globular transfer method. Shielding gas was 25% carbon dioxide and 75% argon. All 1/8 inch thick plates were welded using filler wire of size 0.030 inch. All 3/16 inch thick plates were welded with wire size 0.035 inch.

Line flame heating was used to remove the angular distortion in this study. The torch tip height was maintained constant at 3/16 inch for the 1/8 inch thick plate and 1/4 inch for the 3/16 inch thick plate. The torch velocity was varied, providing a variation in energy input for distortion removal.

The radiagraph, shown in Figure 2-16, was used for both the free-end samples and the stiffened plates to maintain a straight path, control flame velocity, and ensure constant tip height while flame heating.

CHAPTER TWO

PROCEDURE

2.1 Introduction

There are three phases to the experimental part of this thesis.

1. Fabrication and angular distortion measurements of free-end samples,
2. Fabrication of the 3/16" and 1/8" stiffened plates, and
3. Measurement of out of plane distortion in the stiffened plates.

The free-end samples (Figures 2-1 and 2-2) were used to determine the functional relationship between angular distortion removal [d(ri)] and flame heating velocity [v] for each of the mild steel plates used. This functional relationship provided the flame velocity that was used for removing angular distortion from the fabricated stiffened plates.

The stiffened plates (Figure 2-7) are models of ship deck plates. They contain 9 panels, separated by "T" stiffeners. Line heating applied to these plate assemblies, at velocities determined by the functional relationship described above, removed out of plane distortion.

The stiffened plates out-of-plane distortion measurements were taken using a GIDDING & LEWIS milling device (Figure 2-19). The procedure will be described in section 2.4.2.

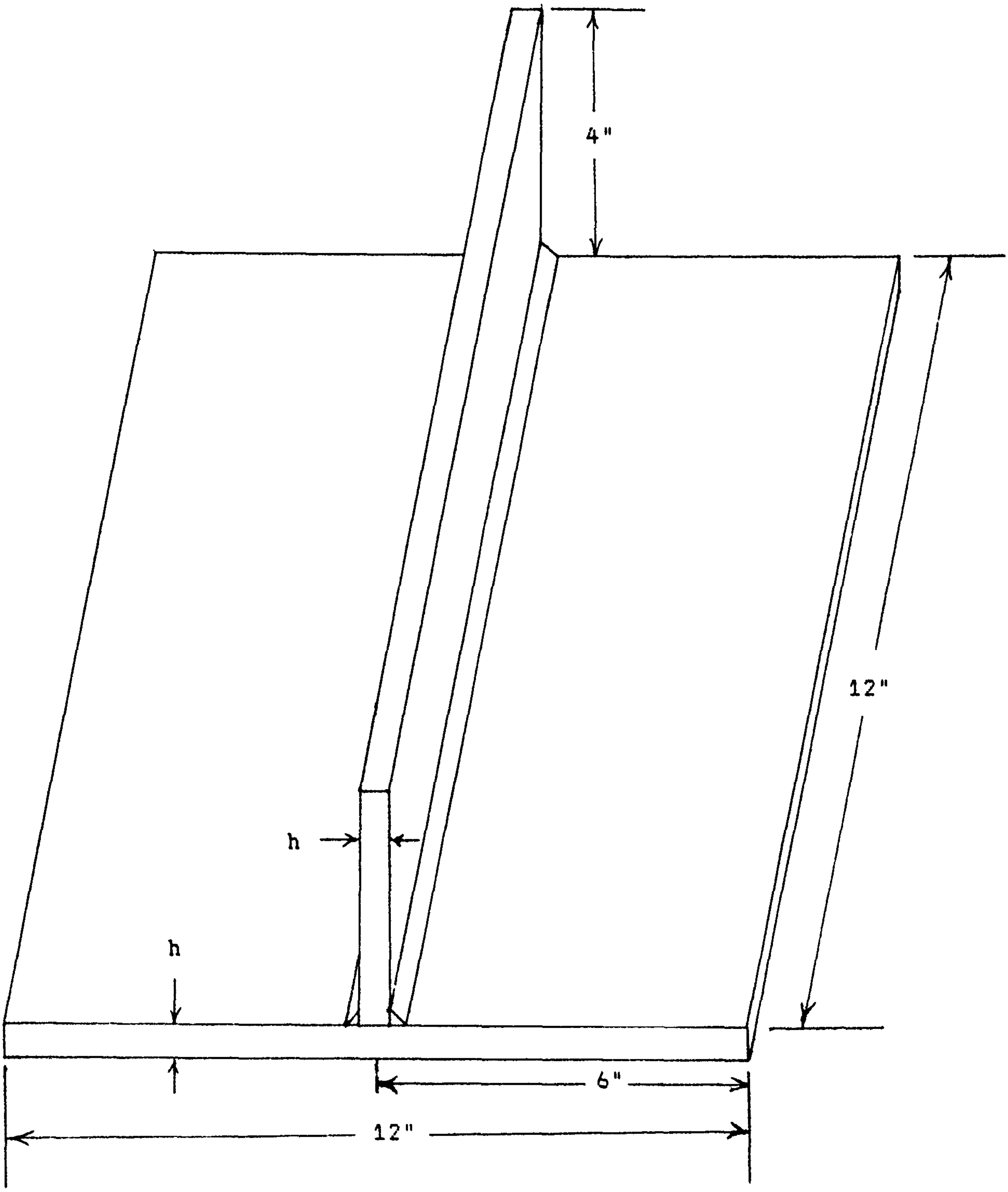


Figure 2-1: FREE-END SAMPLE

Note: h is either 1/8" or 3/16" thick.

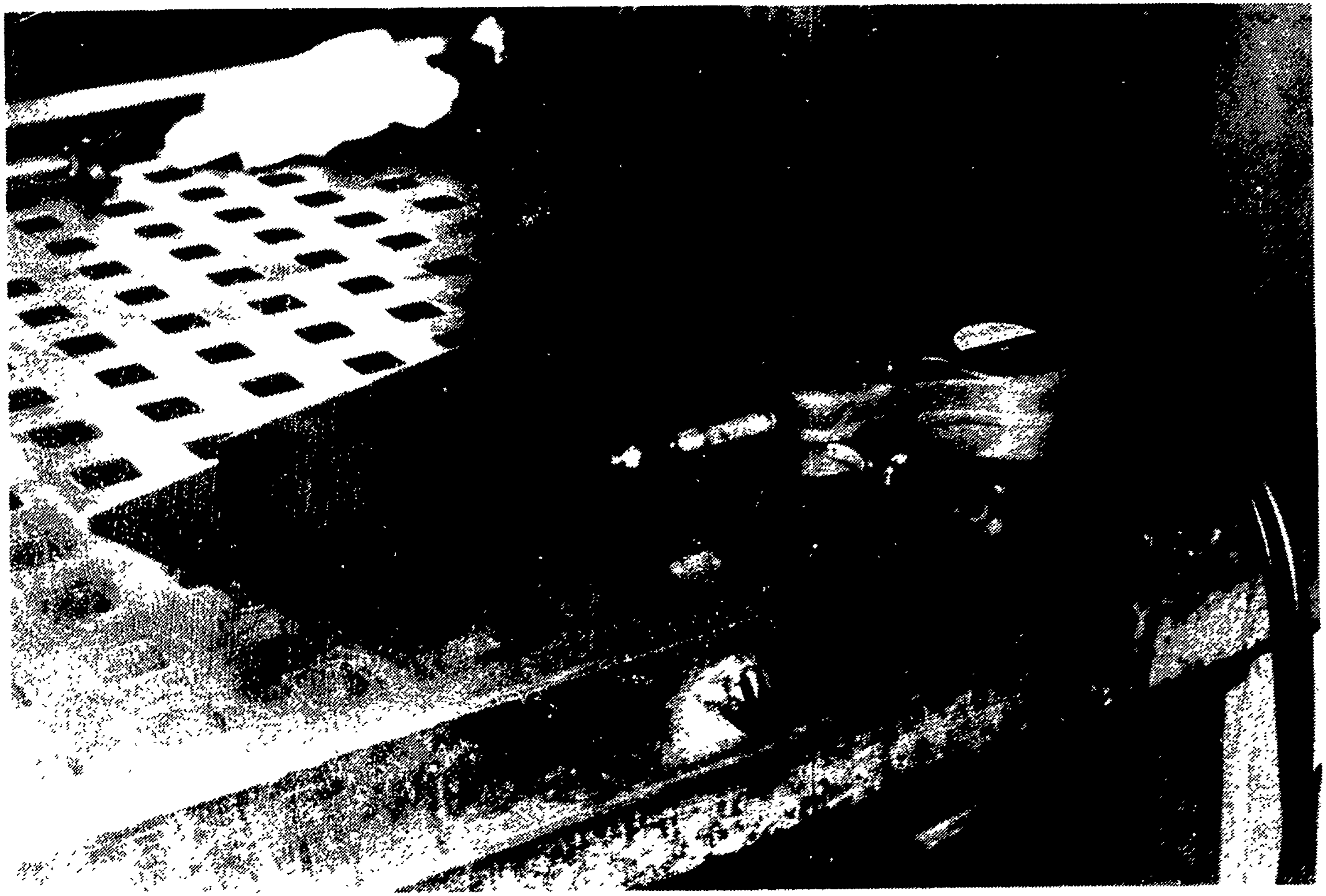


Figure 2-2: FREE-END SAMPLE AND MIG GUN

This chapter contains a discussion of the procedures used in each phase of the experiment along with a description of the equipment used to fabricate and measure distortion in the free-end samples and stiffened plates.

2.2 Description of Specimens

For each plate thickness (1/8 inch or 3/16 inch) there were two types of specimens used (see discussion in section 1.9 above). The free-end samples were made using 12" x 12" x h" plate with a 4" x 12" x h" stiffener fillet welded to the middle of the plate. "h" represents the plate thickness, either 1/8 inch or 3/16 inch. An example of this type of specimen is shown in Figure 2-1. The stiffened plates were fabricated using a 74" x 38" x h" plate fillet welded on one side to a "T" stiffener assembly, using double fillet welds. The stiffeners were welded in a configuration to produce nine (9) panels on each plate. An example of this type of structure is shown in Figure 2-7. Sections 2.2.1 and 2.2.2 describes the procedure used during the fabrication of the free-end samples and the stiffened plates.

2.2.1 Free-end Samples

There were five each of the 3/16 and 1/8 inch thick free-end samples made that provided useful data for this thesis. The plate and stiffener of each sample were made of the same thickness of mild steel, either 1/8 or 3/16 inch. Appendix C provides data on each of the free-end samples. These samples were used to determine the relationship between angular

distortion removed, d(ri), during each line heating pass and flame heating velocity, v. See Figures 2-17 and 2-18.

2.2.2 Stiffened Plates

The 1/8 inch and the 3/16 inch thick stiffened plates were both fabricated to the same dimensions. They only differed in plate and stiffener thickness. In the 3/16 inch sample the "T" stiffeners and plate were made of 3/16 inch thick plating, while the 1/8 inch sample was made of 1/8 inch thick plating.

The "T" stiffeners were fabricated into a 4 transverse by 4 longitudinal matrix, that was 36" wide by 72" long (see Figures 2-3, 2-4, and 2-5), and then welded to the plate, which was 38" wide by 74" long (see Figures 2-6 and 2-7). The plate was cut 2" longer and 2" wider than the web assembly so that the outer stiffeners could be welded to the plate on both sides, thus providing double fillet welds on all stiffeners.

The "T" stiffeners were fabricated using intermittent welds. The stiffener assembly was then welded to the plate using continuous welds. See section 2.3 for the welding procedures used.

2.3 Welding Procedure

This section will discuss the welding equipment used, followed by the welding procedures used for fabricating the free-end samples and the stiffened plates. Both the 1/8 inch and the 3/16 inch specimens were welded using the same procedure, with any exceptions specifically noted.

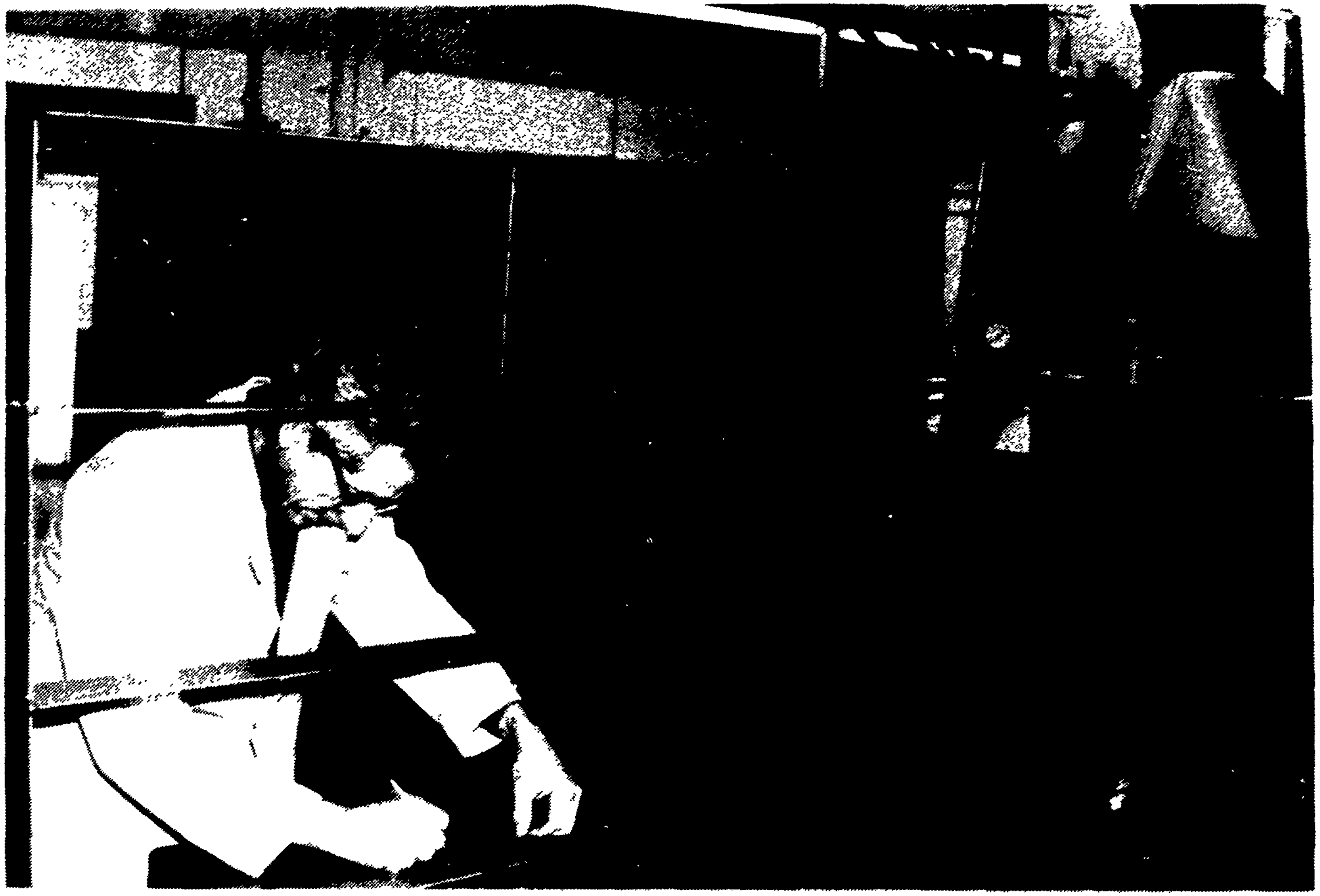


Figure 2-3: FABRICATING STIFFENER WEB COMPLEX FOR STIFFENED PLATE.

Figure 2-4: STIFFENER WEB ASSEMBLY

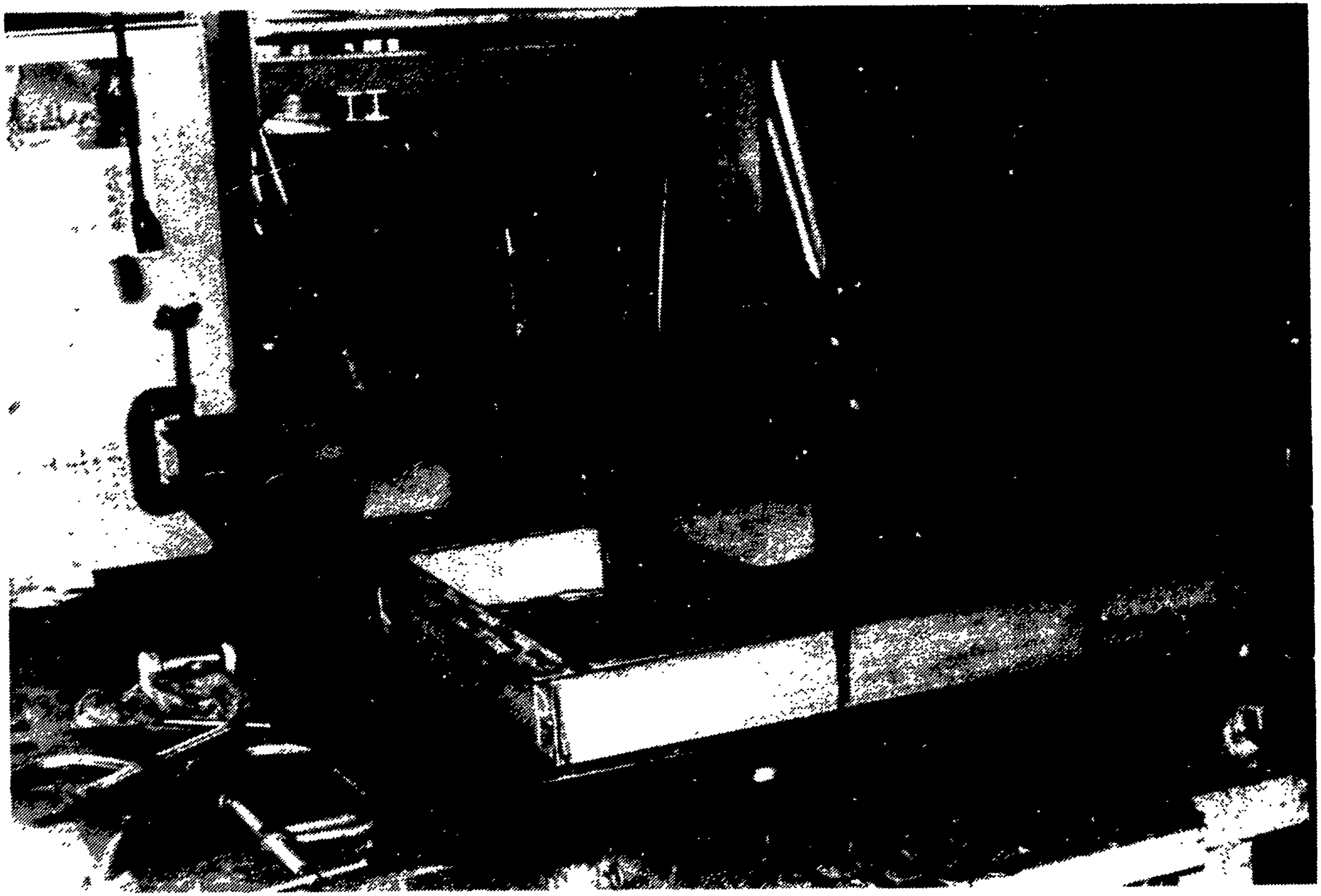


Figure 2-5: "T" STIFFENER ASSEMBLY CLAMPED AND TACK WELDED TO THE PLATE.

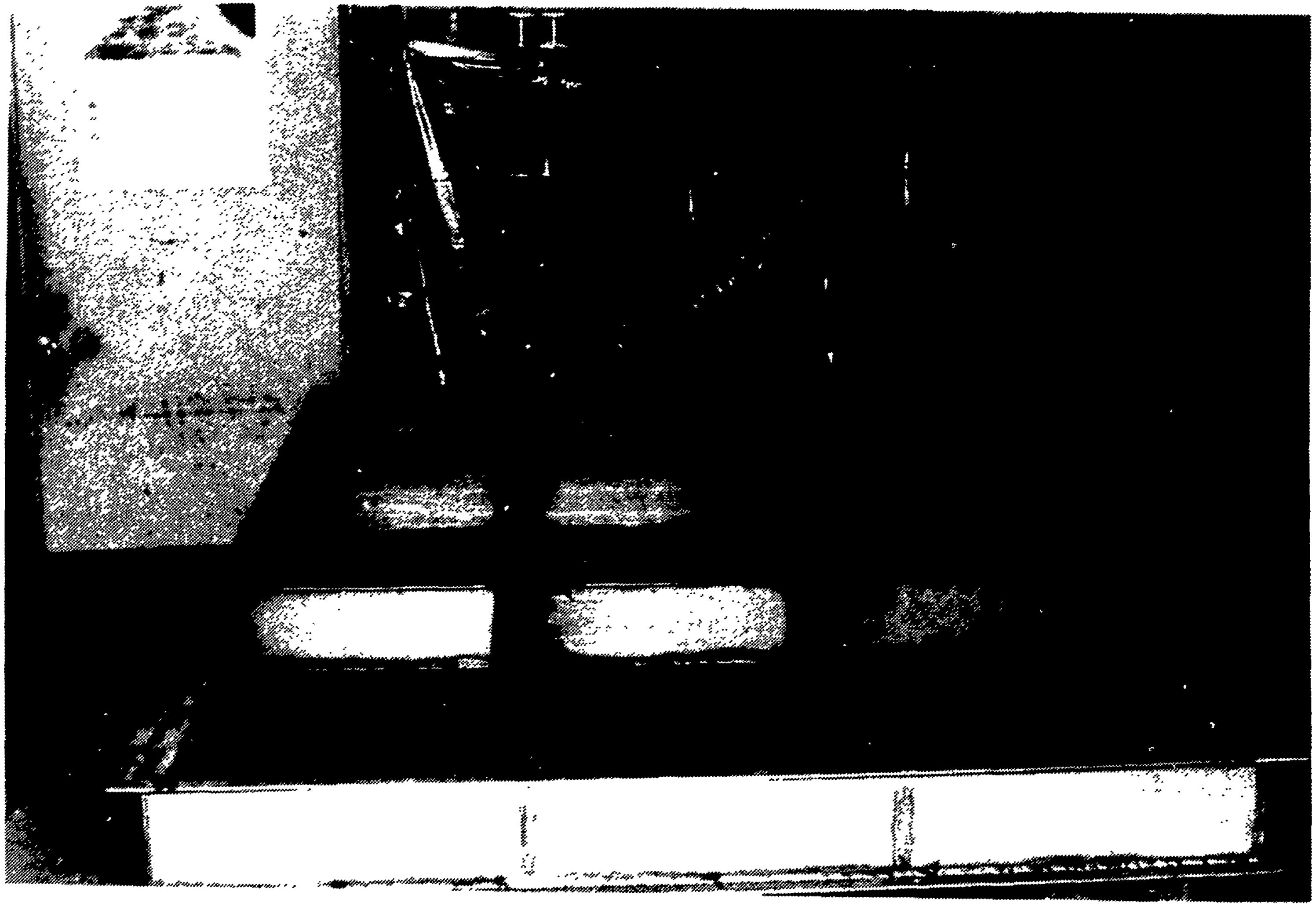


Figure 2-6: BOTTOM VIEW OF STIFFENED PLATE PRIOR TO LINE HEATING.

Figure 2-7: TOP VIEW OF STIFFENED PLATE PRIOR TO LINE HEATING.

2.3.1 Welding Equipment

All welding was performed using the following AIRCO welding machine (Figure 2-8):

MODEL:	2.5 DTR-224-A
STOCK NO.:	1346-5051
SERIAL NO.:	0509668

PRIMARY VOLTAGE:	208/230/460
PRIMARY CURRENT:	33/30/15
KW:	11.4
KVA:	11.9
FREQUENCY:	60Hz, 3-PHASE
SECONDARY VOLTAGE:	35
SECONDARY CURRENT:	250
MAX. O.C.V.:	44
DUTY CYCLE:	100%

The shielding gas was a 25% carbon dioxide 75% argon mixture. The flow rate was maintained at 20 CFH while welding the 1/8 inch thick specimens and 40 CFH while welding the 3/16 inch specimens.

All welds were single pass double fillet welds using the MIG, DCRP, globular transfer method. All welding was done in the horizontal position.

The welding parameters were chosen to provide the maximum amount of angular distortion for the given plate thickness. Watanabe and Satoh [17] experimentally determined the relationship between angular distortion [d] and the heat input parameter [Q/(h*h)], shown in Figure 2-9. This graphical relationship was used, by the author, to determine the parameters (voltage (V), current (I), and flame velocity (v)) that would give maximum angular distortion during welding. Appendix C contains the Q/(h*h) values estimated for each sample.

Figure 2-8: AIRCO WELDING MACHINE WITH SHIELDING GAS TANK.

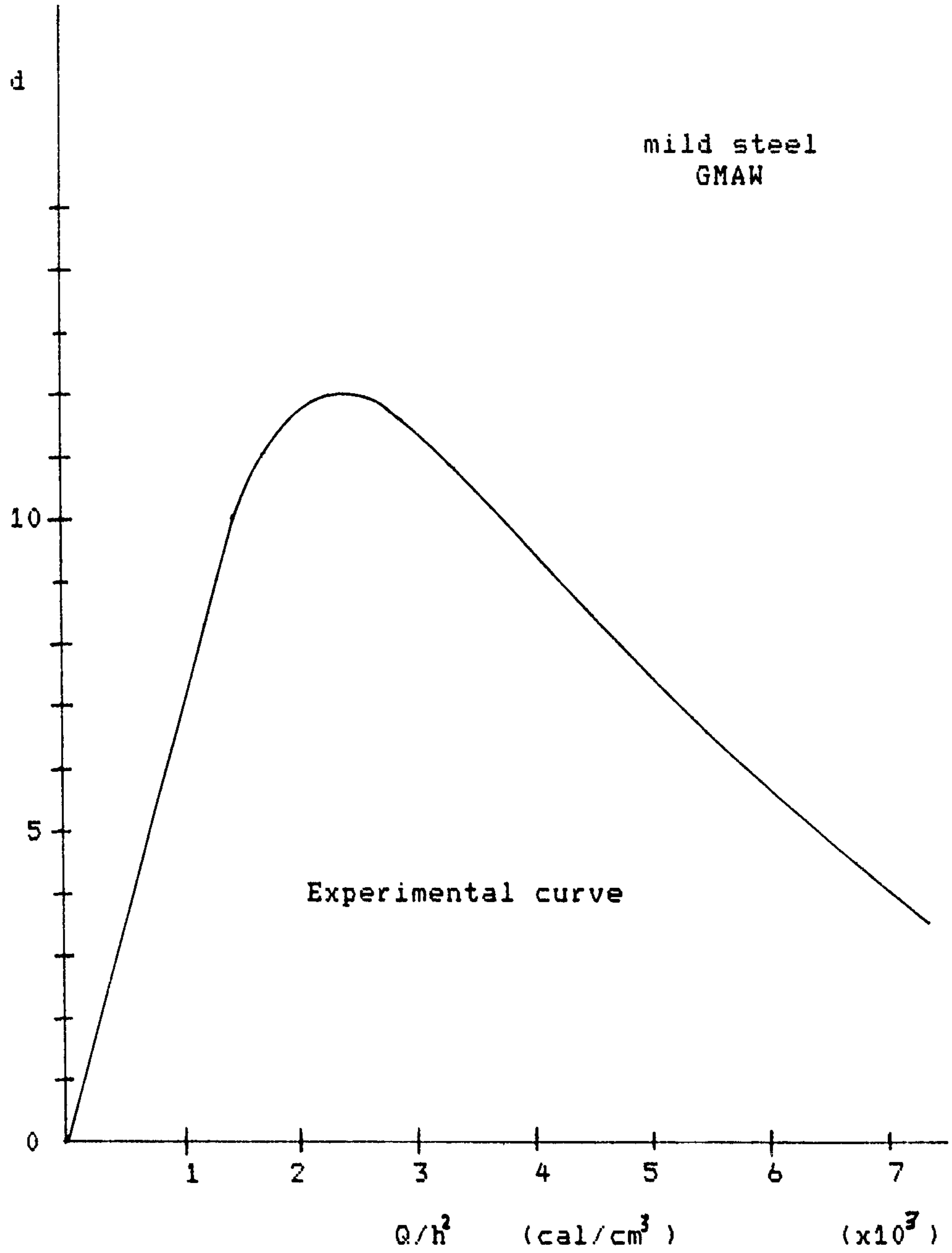


Figure 2-9: ANGULAR DISTORTION, d, vs HEAT INPUT PARAMETER, Q/h^2

2.3.2 Free-end Samples (See Figure 2-1)

There were five 3/16 inch thick free-end samples made (See appendix C) that provided useful data for this thesis. The plate and stiffeners were made of 3/16 inch thick mild steel. The plates were all 12" x 12" x 3/16". The stiffeners were all 4" x 12" x 3/16". The stiffeners were centered on the plates and tack welded. All stiffeners were then welded on one side from right to left. After all samples were given some time to cool the second side of each stiffener was fillet welded from right to left. This provided a similar heat flow pattern for both sides of the sample. The average welding velocity for all five samples was 14.12 in/min (35.86 cm/min). The average weld size (Df) was 0.17332 inches (approx. 11/64 inch). See Figure 2-10 for the definition of Df. The samples were welded at 21.8 volts and 157 amps., which [according to Watanabe and Satoh] gave the optimum angular distortion for the given plate thickness.

There were also five 1/8 inch thick free-end samples made that provided useful data. The plate and stiffeners were made of 1/8 inch thick mild steel. The fabrication procedure used on these samples was the same as that used for the 3/16 inch sample, with the following exception. To prevent buckling, all welds were made from the middle of the sample out towards the edges. The welding sequence is shown in Figure 2-11. Weld passes No. 1 and 2 were completed on all samples and than passes No. 3 and 4 were accomplished. This gave each sample time to cool prior to the last two passes. This procedure

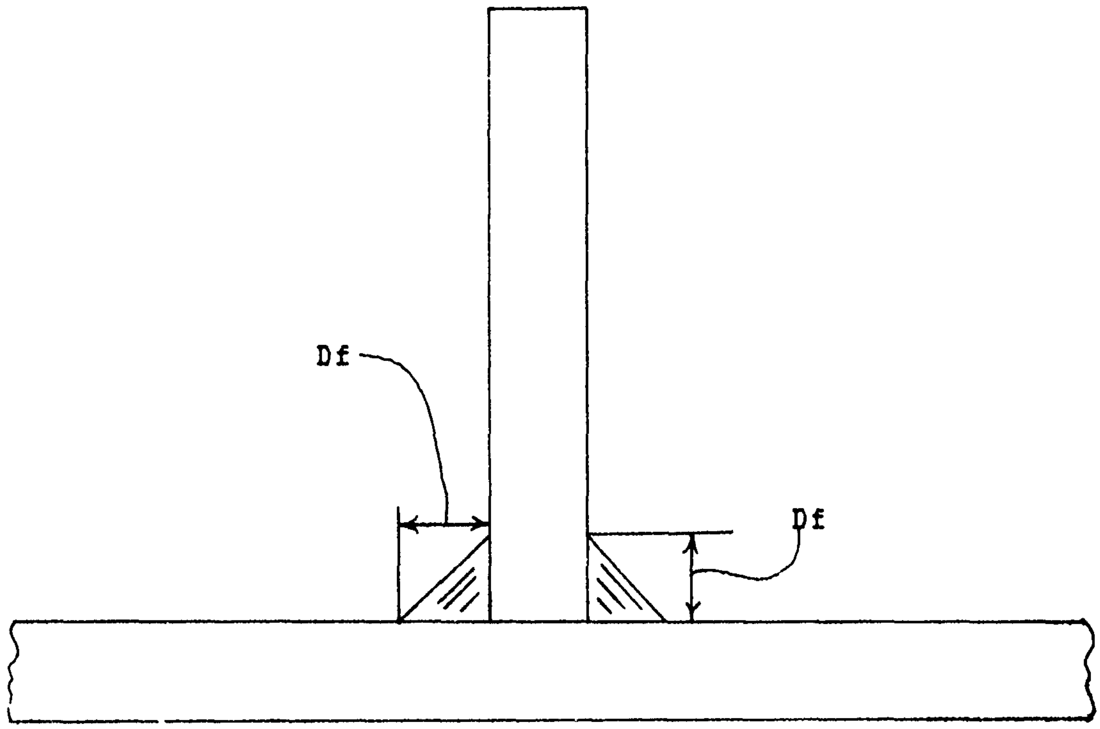


Figure 2-10: DEFINITION OF WELD SIZE (Df)

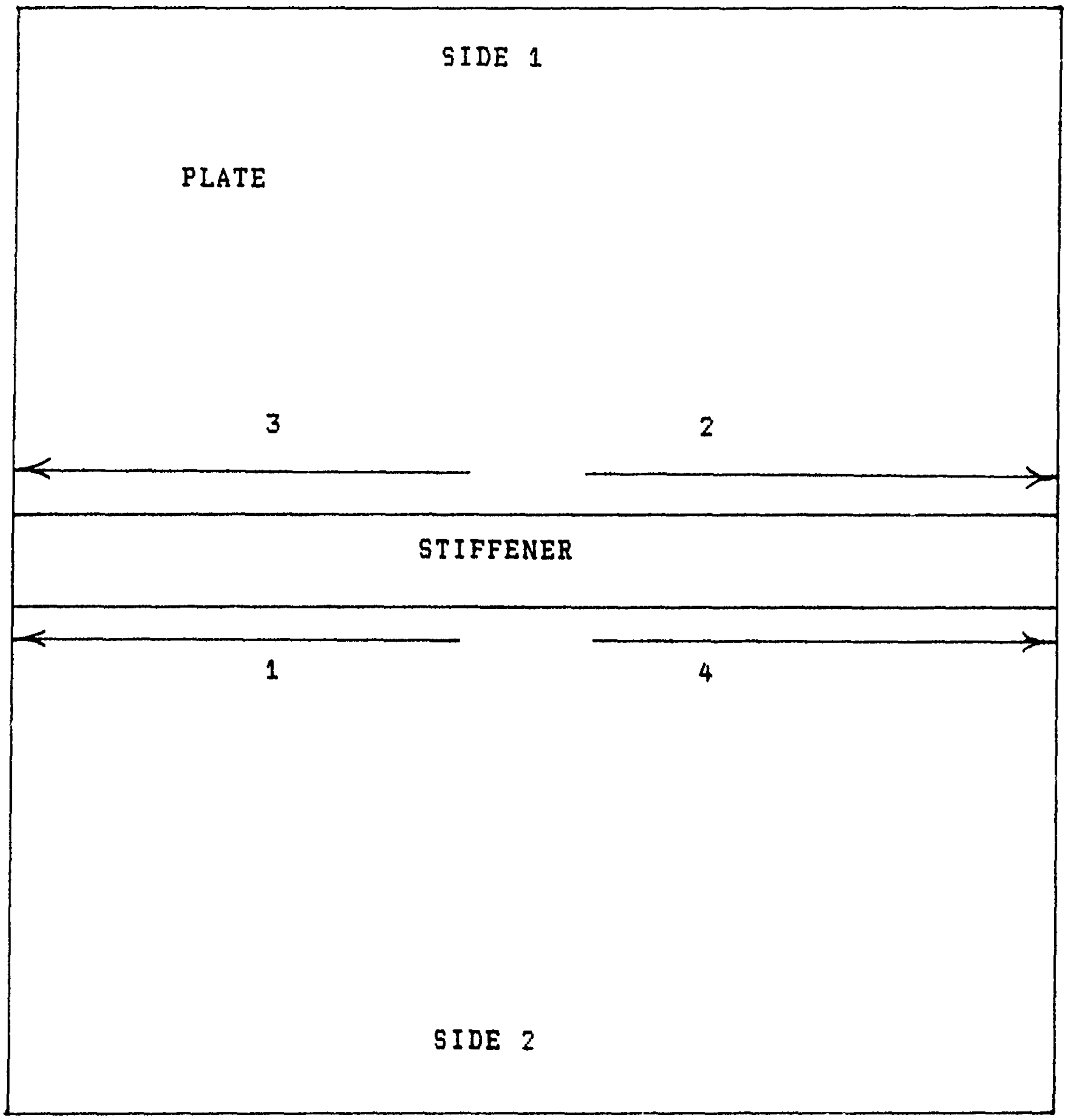


Figure 2-11: WELDING SEQUENCE FOR 1/8" THICK FREE-END SAMPLES

provided samples with minimum buckling distortion. The average welding velocity for all five samples was 16.54 in/min (42.02 cm/min). The average weld size (Df) was 0.105 inches (approx. 7/64 inch). All welds were made at 19 volts and 100 amps, which gave the optimum angular distortion for the given plate thickness.

2.3.3 Stiffened Plates

The sequence for fabricating the stiffened plates was as follows:

1. The "T" stiffeners were fabricated. All webs were welded together, using continuous welds, producing the web assembly (Figures 2-3 and 2-4). The flanges, which were 2 inches wide, were then welded to the web assembly using intermittent welds. This produced the stiffener assembly (Figure 2-5).
2. The stiffener assembly was then centered on the plate, tacked, and welded using continuous welds (Figure 2-6).

Both stiffened plate assemblies were welded using the same procedure. However, there was a different approach used during the final step described above. For the 3/16 inch plate the sequence shown in Figure 2-12 was used while the sequence in Figure 2-13 was used while welding the 1/8 inch stiffener assembly to it's plate. The procedure used on the 1/8 inch plate was recommended by Mr. Fred E. Ingerson [27] to minimize buckling distortion, by minimizing residual stress build up, when welding very thin plates. A random fillet weld

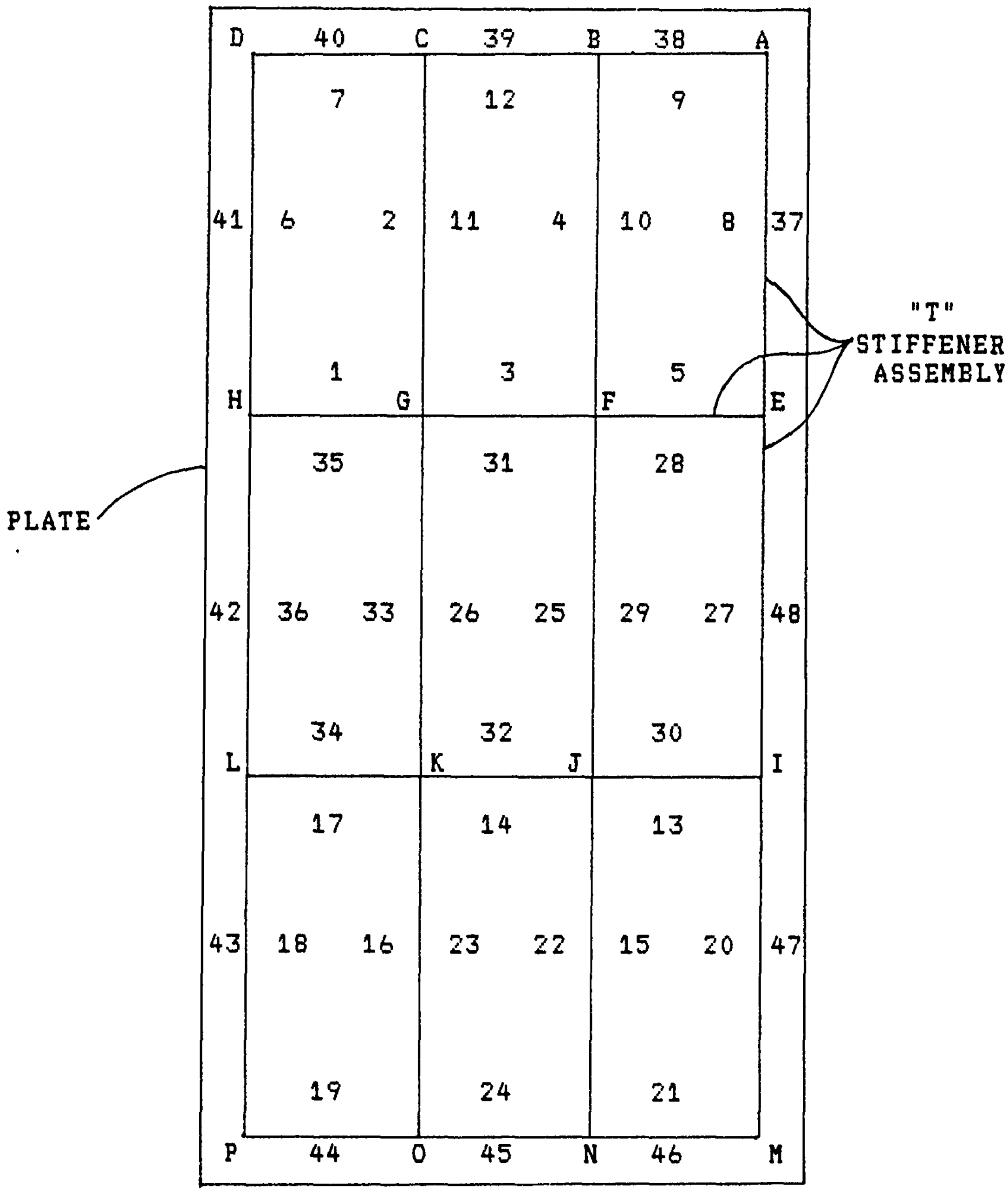


Figure 2-12: WELDING SEQUENCE USED TO WELD 3/16" "T" STIFFENER ASSEMBLY TO 3/16" PLATE

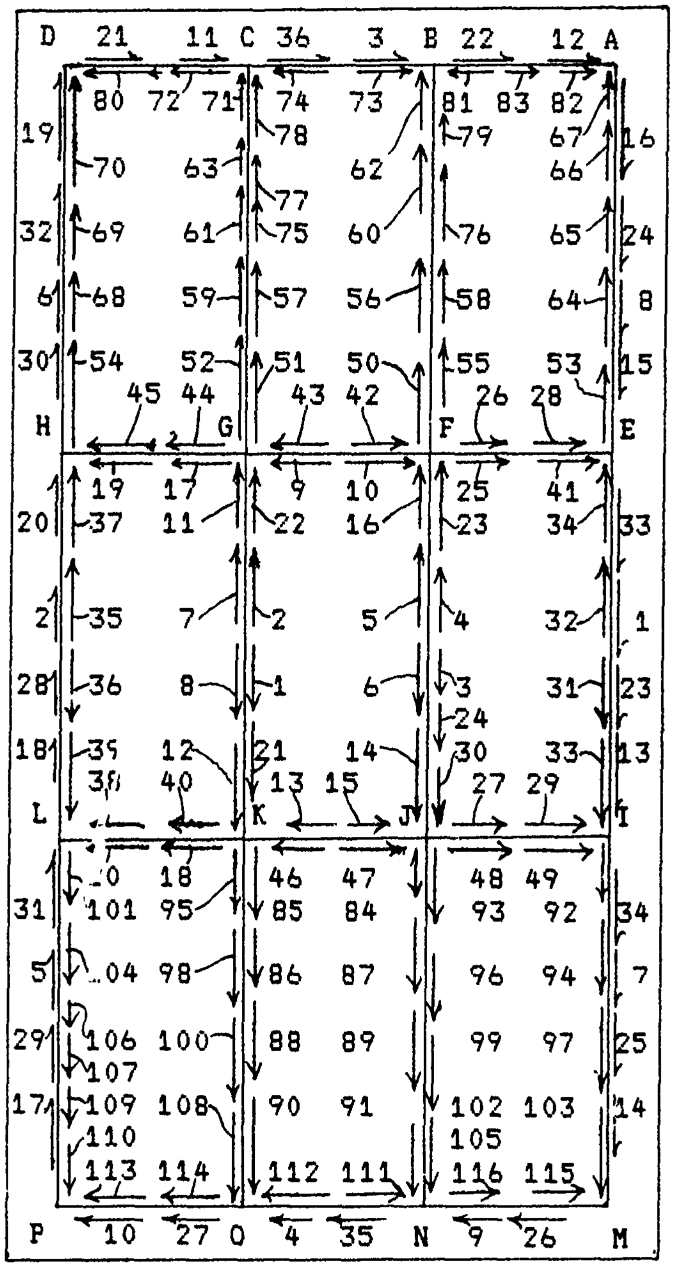


Figure 2-13: WELDING SEQUENCE USED TO WELD 1/8" "T" STIFFENER ASSEMBLY TO 1/8" PLATE

sequence was used but welding was started close to the middle of the plate and always welded towards the edge. Also, the length of each weld was limited to 6 inches to limit heat build up, thus minimizing thermal stresses.

The 3/16 inch model was welded with the following parameter settings:

voltage:	23.5
current:	135 amps
filler wire diameter:	0.035 inches
filler wire speed:	between settings 5 and 6
turns setting:	28.75
tap slope setting:	No. 8
shielding gas flow rate:	40 CFH
welding velocity:	approx. 14in/min (35.6cm/min)

The 1/8 inch model was welded with the following parameter settings:

voltage:	19
current:	105 amps
filler wire diameter:	0.030 inches
filler wire speed:	between settings 5 and 6
turns setting:	23
tap slope setting:	No. 6
shielding gas flow rate:	20 CFH
welding velocity:	approx. 16.5in/min (42cm/min)

2.4 Experimental Procedure

This section describes the procedure used to:

1. determine the functional relationship between the angular distortion removed [d(ri)] and the flame straightening velocity (v) used during line heating of the free-end samples,
2. measure out-of-plane distortion [D(i,j)] in the stiffened plates, and
3. apply line heating to the stiffened plate.

2.4.1 Experimental Determination of the d(ri) vs. v Relationship

After the free-end samples were welded, out-of-plane distortion measurements [H] were taken using the calipers shown in Figure 2-14. The free-end samples were clamped to a calibrated flat surface and three out-of-plane distortion [H] readings were taken along the raised edge. The sample was then rotated 180 degrees reclamped and three more distortion readings were taken. The average out-of-plane distortion after welding [H(aw)] was then calculated for each sample and used by the following equation

$$d(w) = 0.5*\arctan\left[\{H(aw) - h\}/\{0.5*L\}\right]$$

where, d(w) = angular distortion after welding

h = plate thickness

L = plate width

to determine the angular distortion produced at the stiffener do to the double fillet weld. See Figure 2-15 for a pictorial description. Values calculated for each sample are found in Appendix C under "A. After Welding".

The samples were next attached to a flat welding table and line heated, on the back side of the fillet weld, using an oxyacetylene torch connected to a radiagraph cart (see Figure 2-16). Each sample was line heated at a different velocity. The radiagraph contains a variable speed control that ranges from 5.0 in/min at setting "A" to 47.0 in/min at setting "W". The velocities used were distributed through this range, with the slowest velocity fast enough to prevent the metal surface from melting while heating. The actual velocities used for

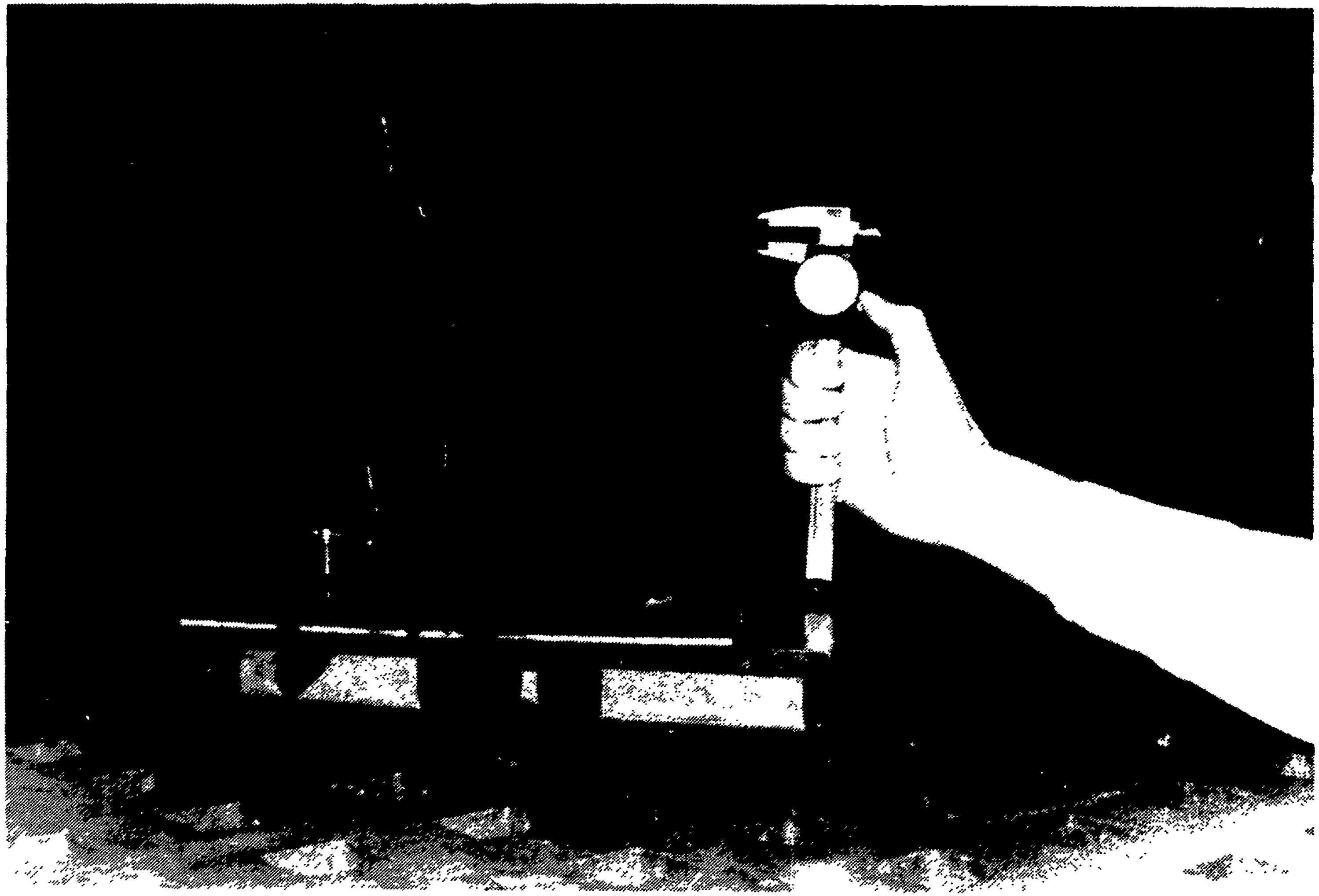
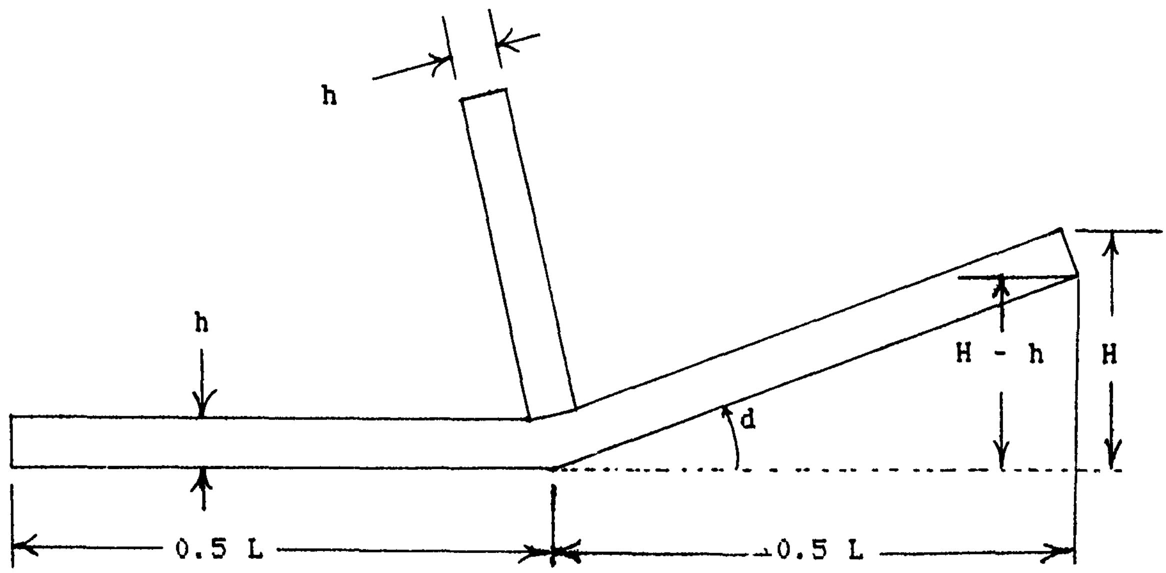


Figure 2-14: OUT-OF-PLANE DISTORTION [H] MEASUREMENT OF FREE-END SAMPLE.



d = 0.5 * arctan ((H - h)/(0.5 * L))

Figure 2-15: ANGULAR DISTORTION DEFINITION FOR FREE-END SAMPLES

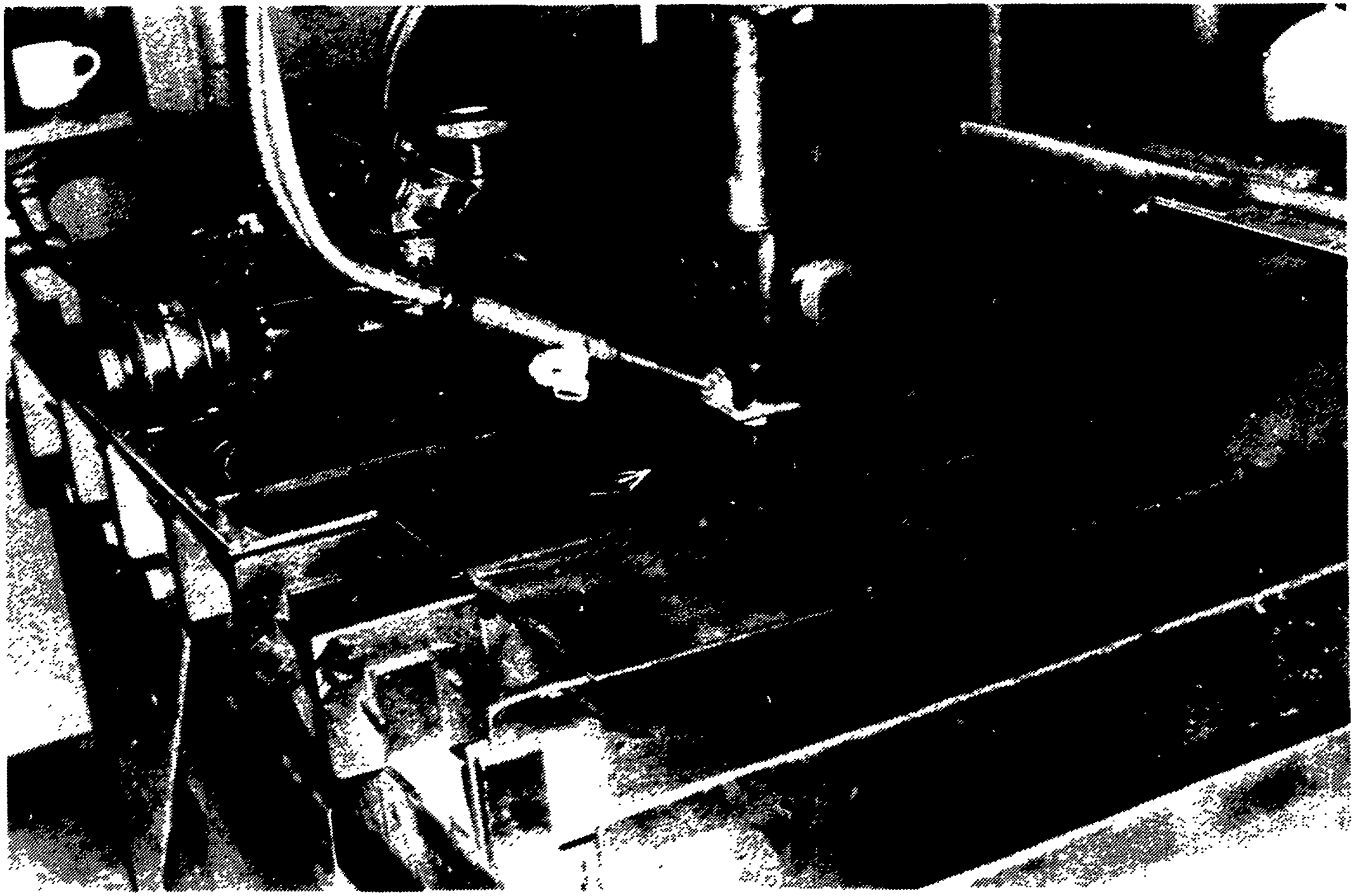


Figure 2-16: SET UP FOR ANGULAR DISTORTION REMOVAL, d, IN FREE-END SAMPLES.
[NOTE: SAME SET UP WAS USED FOR DISTORTION REMOVAL ON STIFFENED PLATES]

each of the samples are given in Appendix C under "B. After First Flame Heating Pass".

For all line heating the gas pressures, torch height, and method of attaching the sample to the heating table were constants.

The 3/16 inch thick samples were line heated under the following conditions:

torch height:	1/4 inch
oxygen (O2) pressure:	5 psig
acetylene (C2H2) pressure:	5 psig
torch:	ARCO style 4890
	tip type # 144
	tip size # 5

The 1/8 inch thick samples were all line heated under the following conditions:

torch height:	3/16 inch
O2 pressure:	3 psig
C2H2 pressure:	3 psig
torch:	ARCO style 0400
	tip style # 91
	tip size # 3

After line heating, out-of plane distortion readings [H(a1)] were again taken as described above (Figure 2-14), angular distortion after the first heating pass [d(a1)] was calculated (see equation in Appendix C), and angular distortion removed during the first heating pass [d(r1)], d(r1) = d(w) - d(a1)] was calculated. These values are recorded in Appendix C under the heading "B. After the First Flame Heating Pass". Each sample was then heated a second time, at the same velocity as their first pass, and distortion readings [H(a2) measured, d(a2) calculated, and d(r2) = d(a1) - d(a2) calculated] were recorded in Appendix C under "C.

After The Second Flame Heating Pass".

Based on this data Figures 2-17 and 2-18 were plotted. These graphs provide the needed relationships between angular distortion removal [d(ri] and flame heating velocity [v] for mild steel which was used to remove the out-of-plane distortion in the stiffened plates. d(r3) and d(r4), in Figure 2-18, were assumed functions based on the relationship between d(r1) and d(r2), and from previous research results [5, 26].

2.4.2 Measurement of Out-of-Plane Distortion in the Stiffened Plates

Out-of-plane distortion [D(i,j)] measurements of the stiffened plates were made after welding and after each flame straightening pass. The GIDDING & LEWIS milling device shown in Figure 2-19 was used. The mill arm, extended and locked into position, held the dial gauge/indicator (range -0.500 to 0.500 inch, with markings at 0.001 inches, and accuracy of 0.001 inches) used to measure out-of-plane distortion (Figure 2-20). The stiffened plate was clamped to the table so that it did not move relative to the table during machine operation. The tables vertical measured accuracy was within 0.002 inches. The table was then moved in, out, left, or right; which carried the stiffened plate under the dial indicator where measurements were taken.

The dial indicator was zeroed at a reference point. All distortion measurements were then taken relative to this reference point. A grid system was established as shown in

Figure 2-17: 3/16'' SAMPLES

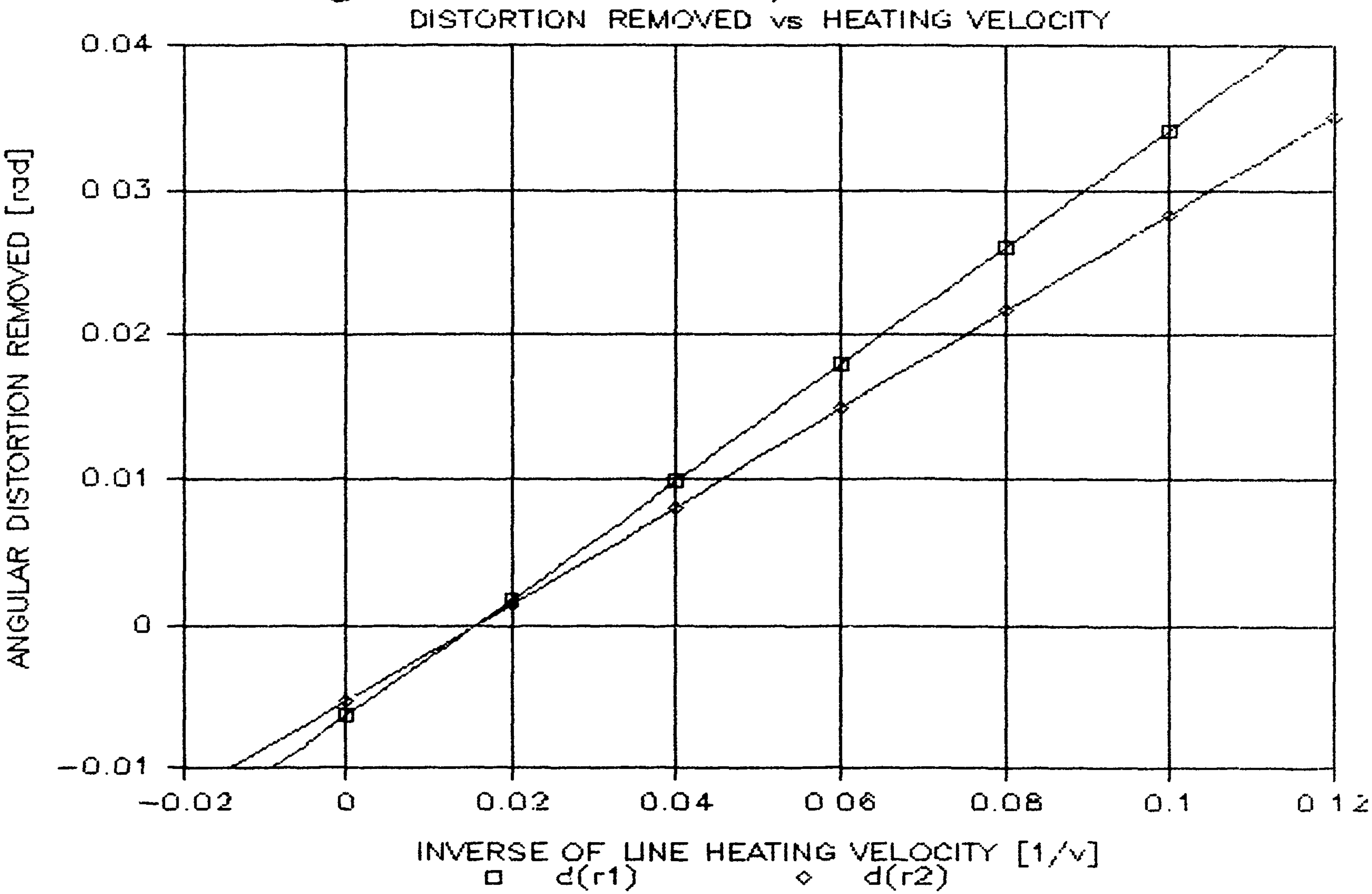
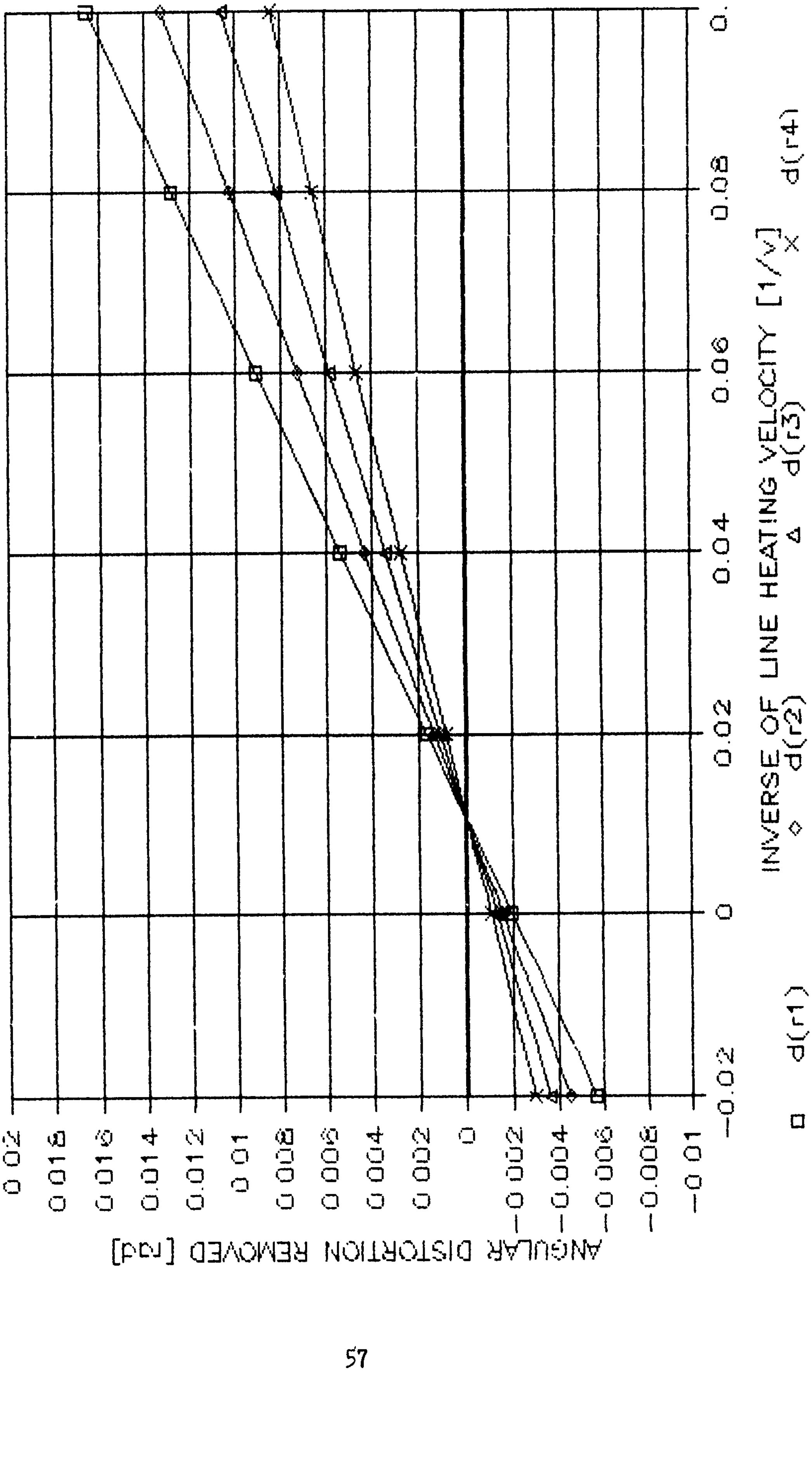


Figure 2-18: 1/8" SAMPLES

DISTORTION REMOVED vs HEATING VELOCITY



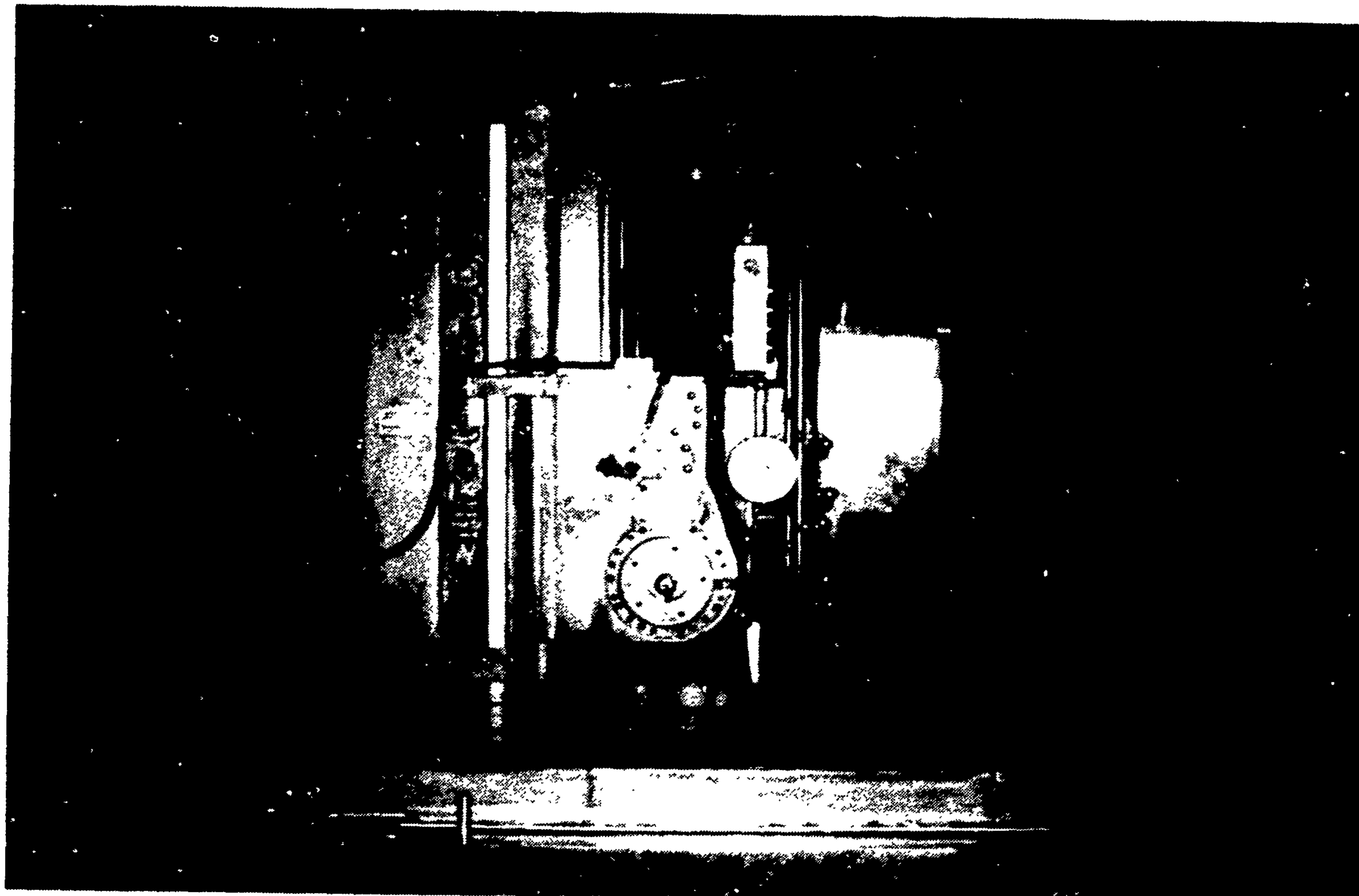


Figure 2-19: GIDDING & LEWIS MILLING DEVICE USED TO MEASURE OUT-OF-PLANE DISTORTION OF THE STIFFENED PLATES.

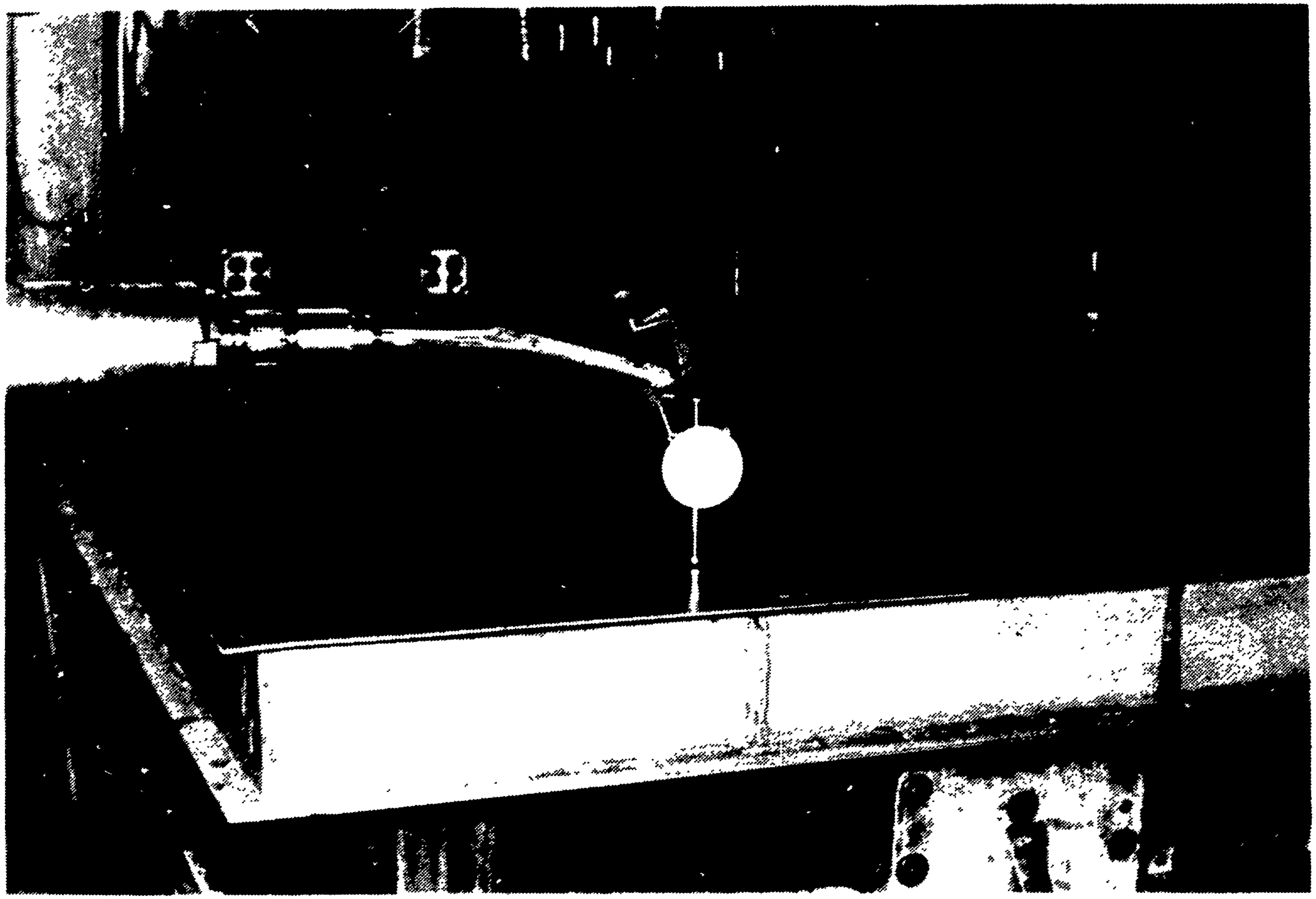


Figure 2-20: SET UP FOR OUT-OF-PLANE DISTROTION, $D(i,j)$, MEASUREMENT OF STIFFENED PLATE.

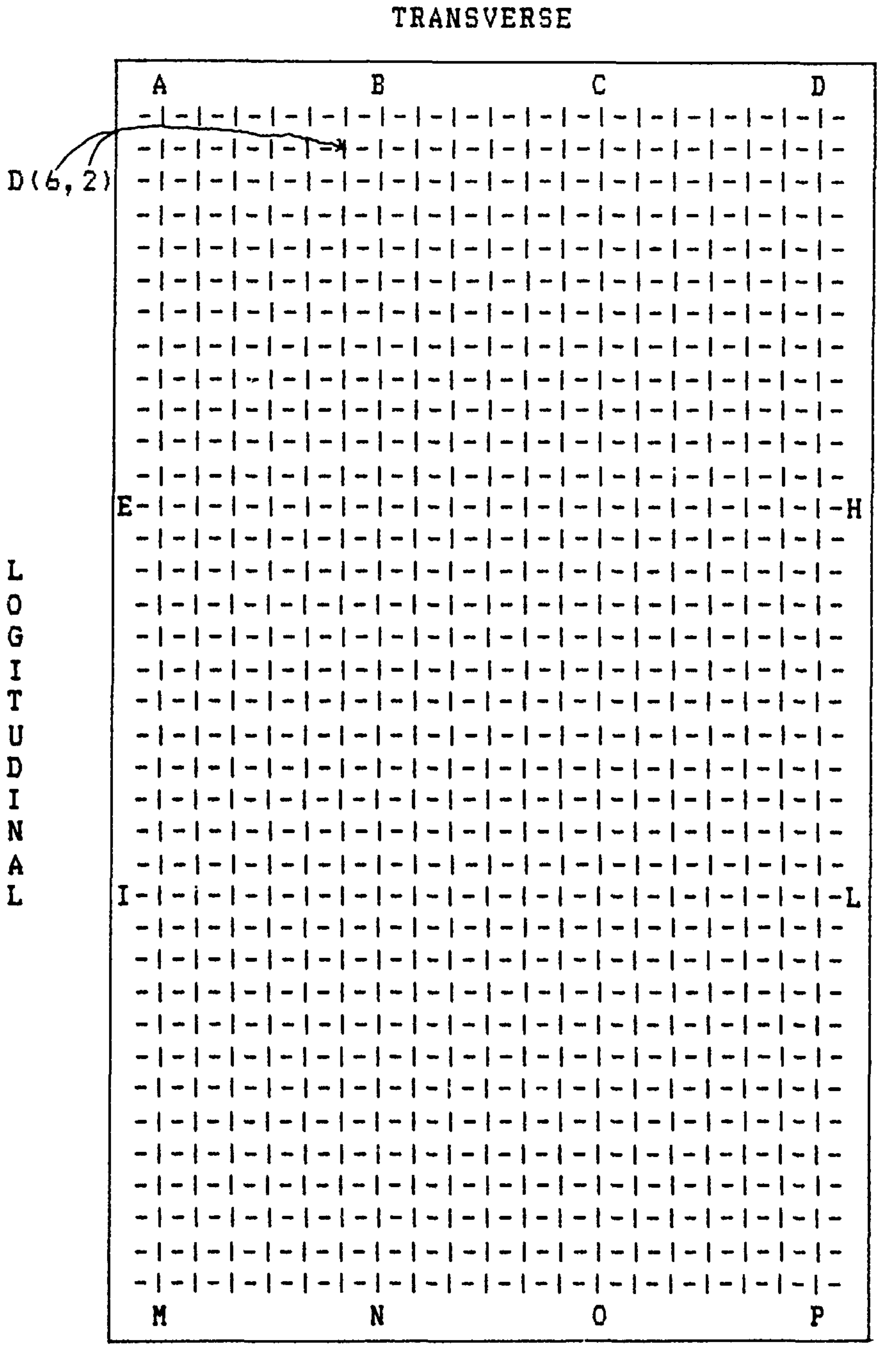
Figures 2-20 and 2-21. Distortion measurements could then be taken at the intersection of each of the grid lines by moving the table under the dial indicator.

Two sets of distortion readings were taken using the 3/16 inch thick stiffened plate, prior to any flame heating. The indicated deflections never changed more than 0.003 inches, thus all readings taken were assumed to be accurate to within 0.003 inches.

The first 7 sets of deflection readings were taken at each of the grid intersections shown in Figure 2-21. The remaining sets of deflection readings had distortion measurements recorded every 2 inches on the stiffener lines and on the mid panel lines only. (See Figure 2-22) The reduction in the number of readings was do to time and cost restraints.

2.4.3 Stiffened Plate Straightening Technique

Each plate contained 9 panels and was labeled as shown in Figure 2-23. One panel was line heated during a flame heating session. The radiagraph and parameter settings used for line heating the free-end samples, as presented in section 2.4.1 above, were also used on the plates. Line heating was applied along each of the four stiffeners, at a distance of one fillet weld width [Df] towards the panel side of the stiffener (see the broken lines in panel 5 of Figure 2-23). Next, readings on the entire plate were taken and recorded. The next panel was then flame heated and measured. This procedure was repeated until all panels were heated once and most panels



D(t,L) = distortion at grid crossing (t,L)
t = transverse spacing
L = longitudinal spacing

[Example, see D(6,2) above]

Figure 2-21: MEASUREMENT GRID ON TOP SURFACE OF STIFFENED PLATE

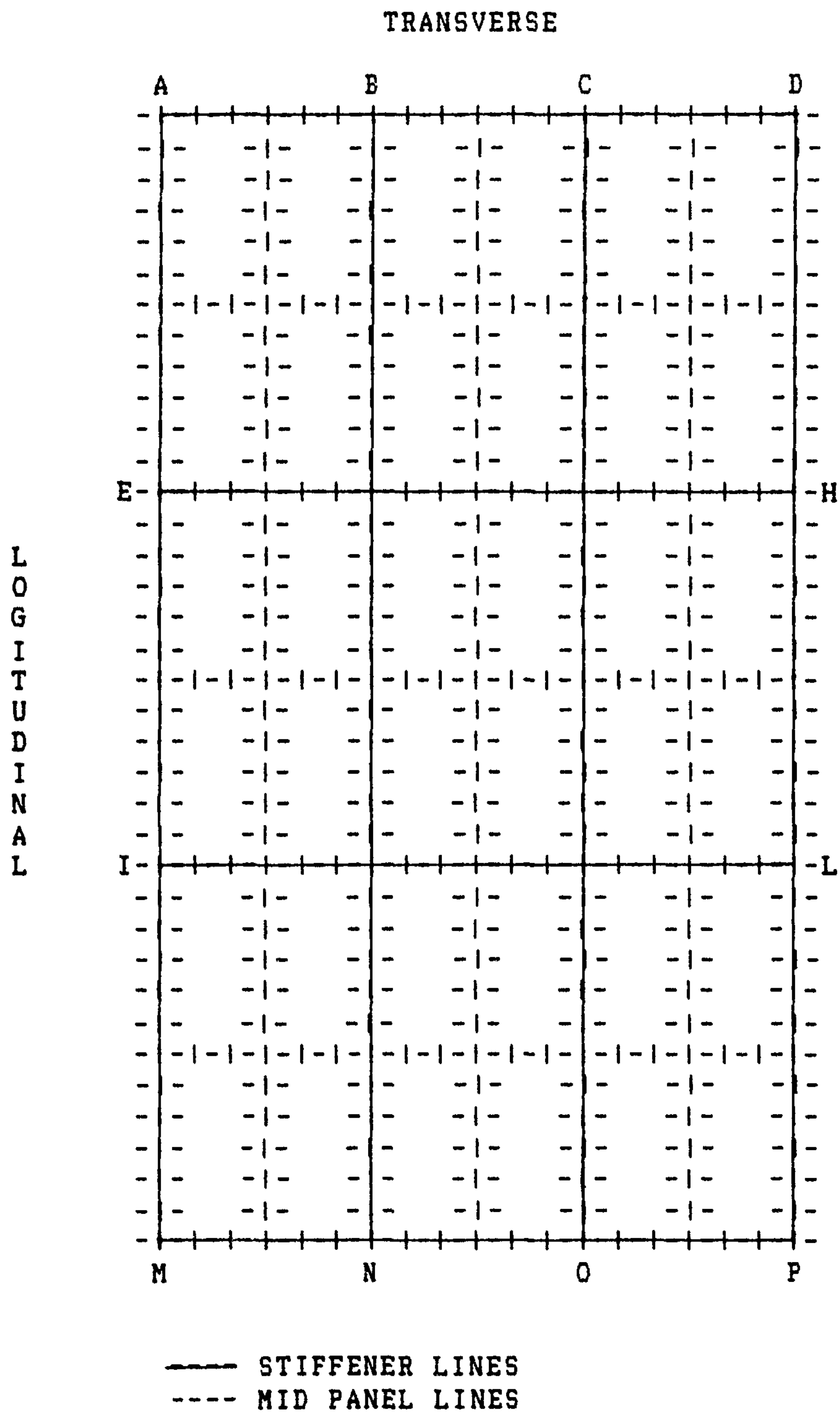


Figure 2-22: MEASUREMENT GRID CONTAINING STIFFENER LINES AND MID PANEL LINES ONLY.

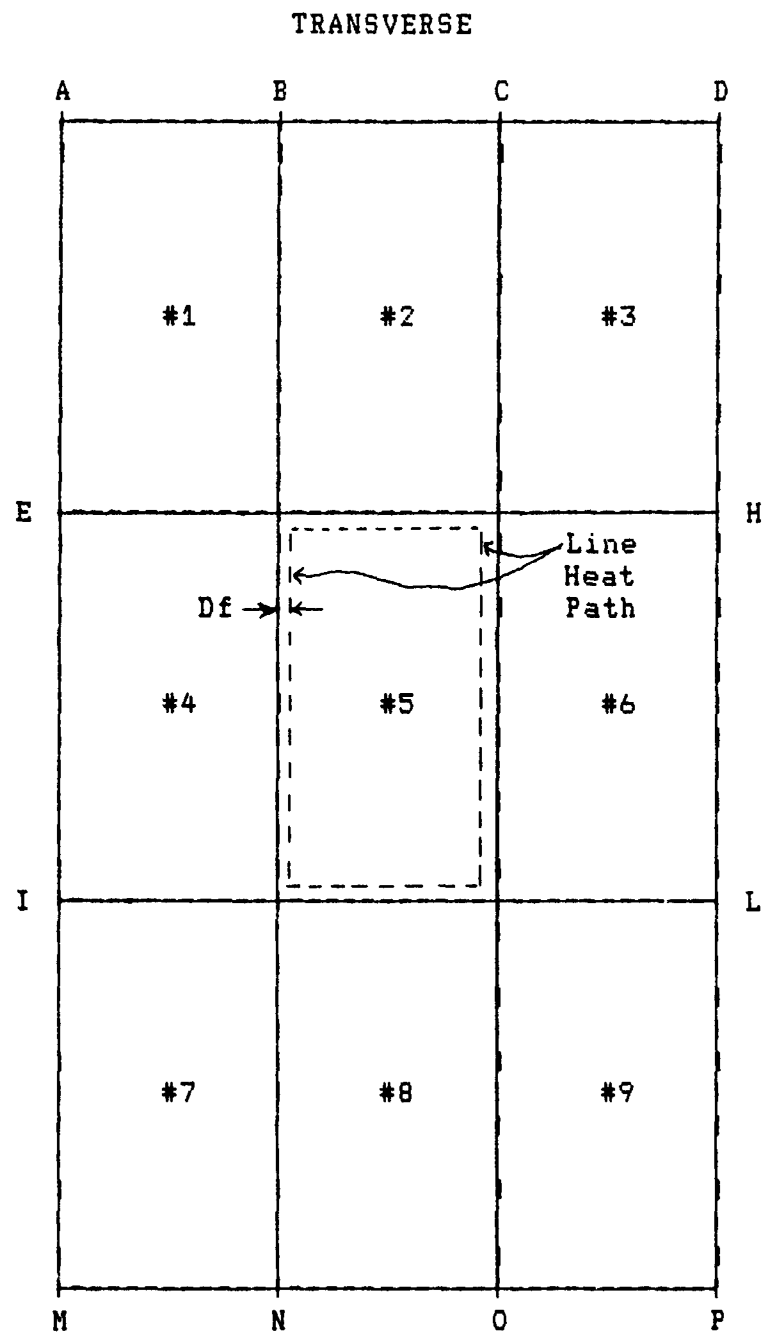


Figure 2-23: PANEL NOMENCLATURE USED IN THIS PAPER

were heated twice.

For the 3/16 inch thick plate, the first panel heated was #5, followed in order by #4, #2, #8, #6, #1, #7, #3, and #9. The order of heating for the second pass and for the line heating passes on the 1/8 inch thick plate are as indicated in Tables 2-1 and 2-2.

Line heating was always applied in a direction away from the center of the plate, to reduce the amount of residual stress build up. The direction that line heating was applied on each of the panels is shown by arrows in Figures 2-24 and 2-25. The order of applying line heat, while heating each panel, is indicated by the numbers next to each of the lines found in Figures 2-24 and 2-25. For example, when line heating panel #8 on the 3/16 inch thick plate (Figure 2-24) the first line heating pass was directed from J to K at a distance Df from the stiffener. The second heating was from J to N, the third from K to O, and the last from N to O. Note that all line heating paths are directed, as much as possible, away from the center of the plate.

2.4.3.1 Calculation of Line Heating Velocity

The procedure followed in this section is based on the assumption that the middle strip of panel, in both the longitudinal and transverse direction, behaves as if it were unrestrained. That is, it reacts to line heating similar to the free-end samples discussed above. Thus, to determining the line heating velocity, the angular distortion at mid panel is measured and this value is entered into the appropriate

TABLE 2-1

ORDER OF APPLYING LINE HEAT TO THE 3/16" STIFFENED PLATE

SEQUENCE	1ST PASS	2ND PASS
1ST	5	5
2ND	4	6
3RD	2	2
4TH	8	8
5TH	6	1
6TH	1	3
7TH	7	7
8TH	3	9
9TH	9	

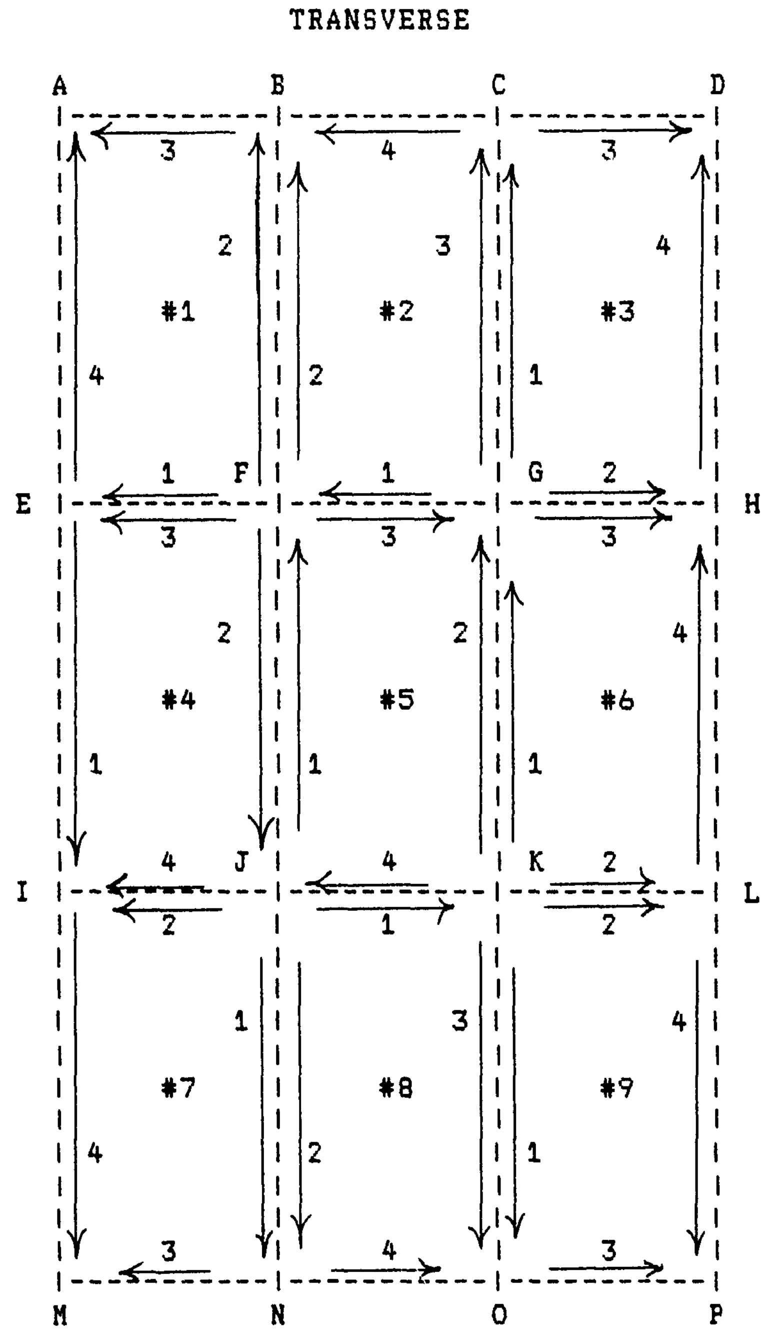
NOTE: PANEL #4 WAS NOT LINE HEATED ON THE SECOND PASS.
[PANEL #4 HAD EXCESS BUCKLING]

TABLE 2-2

ORDER OF APPLYING LINE HEAT TO THE 1/8" STIFFENED PLATE

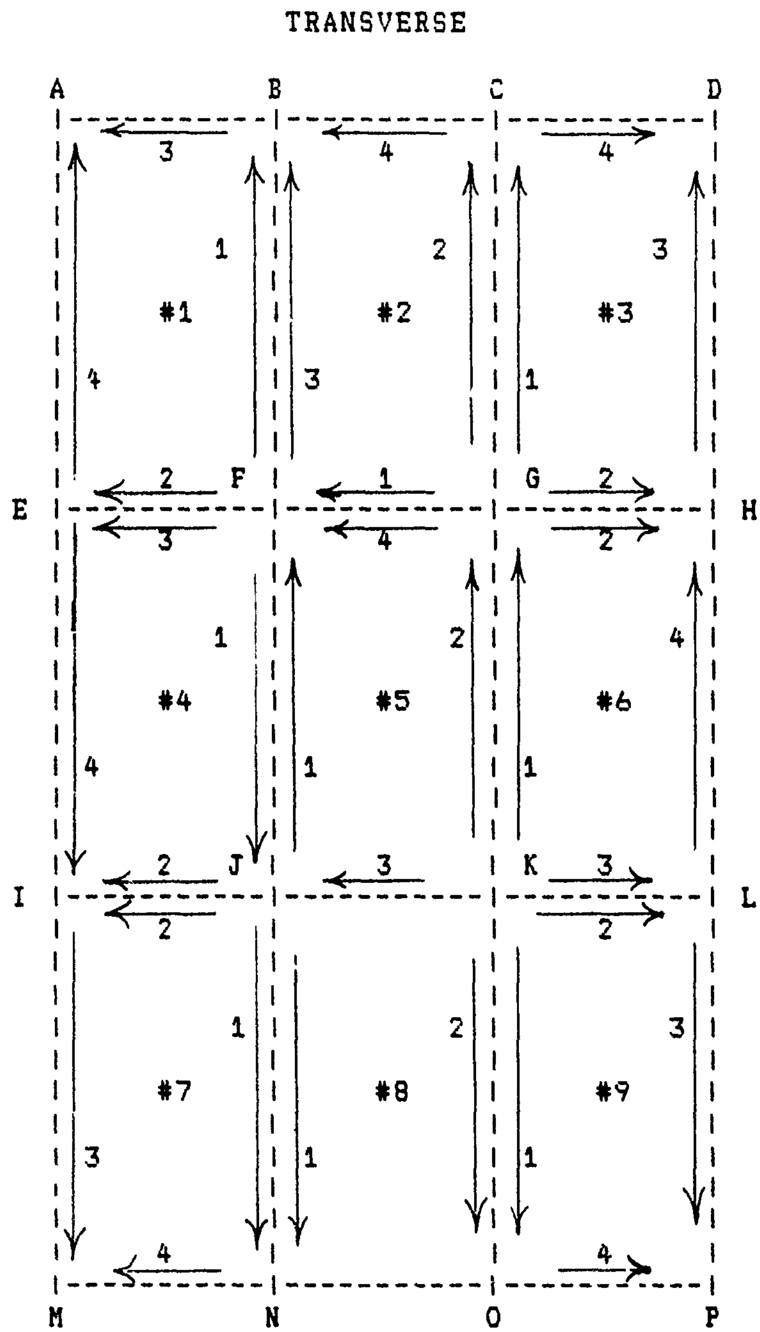
SEQUENCE	1ST PASS	2ND PASS	3RD PASS	4TH PASS
1ST	5	5	1	7
2ND	4	4	7	1
3RD	6	1		
4TH	2	7		
5TH	8			
6TH	3			
7TH	1			
8TH	7			
9TH	9			

NOTE: After the first pass panels #2, #3, #6, and #8 had minimal out-of-plane distortion remaining or buckled and were thus not line heated on the following heat passes. Panel #9 was damaged while measuring the plate after heating panel #5 the second time and was thus not heated again. Panels #7 and #1 were each heated 4 times. On the first pass their out-of-plane distortion increased, due to excessive heat energy added, and passes two, three, and four were accomplished at speeds greater than the critical velocity to see if distortion could be removed.



NOTE: The arrows indicate the direction of applying line heat and the numbers next to each arrow signifies the sequence of applying heat to each panel.

Figure 2-24: 3/16" PLATE LINE HEATING PATTERN



NOTE: The arrows indicate the direction of applying line heat and the numbers next to each arrow signifies the sequence of applying heat to each panel.

Figure 2-25: 1/8" PLATE LINE HEATING PATTERN

graph (Figure 2-17 or 2-18) to obtain the line heating velocity for that pass.

The velocity of the radiagraph for each line heating run was calculated based on the out-of-plane distortion measurements obtained during the previous recording session. Refer to Figure 2-26 for deflection readings and Figures 2-27 and 2-28 for graphs of the mid panel line deflections used in the following discussion. Figure 2-26 contains the after welding out-of-plane distortion readings recorded for panel #5 of the 3/16 inch thick plate. In other words, this is the data used when calculating the velocity for removing distortion in panel #5 when heating panel #5 for the first pass. This data is also found in Appendix D. The steps used for calculating the line heating velocities for each pass are as follows:

1. Calculate the reference angle. This is the slope of the panel from one side stiff ner to the other side stiffener. There are two reference angles, one longitudinal and one transverse. The reference angles was calculated by

   d(rL5) = the longitudinal reference angle for panel #5 in radians (see Figure 2-29)

   d(rL5) = arctan {change in displacement/panel length}

   d(rt5) = the transverse reference angle for panel #5 in radians

   d(rt5) = arctan {change in displacement/panel width}.

These equations, with appropriate panel numbers in

TRANSVERSE

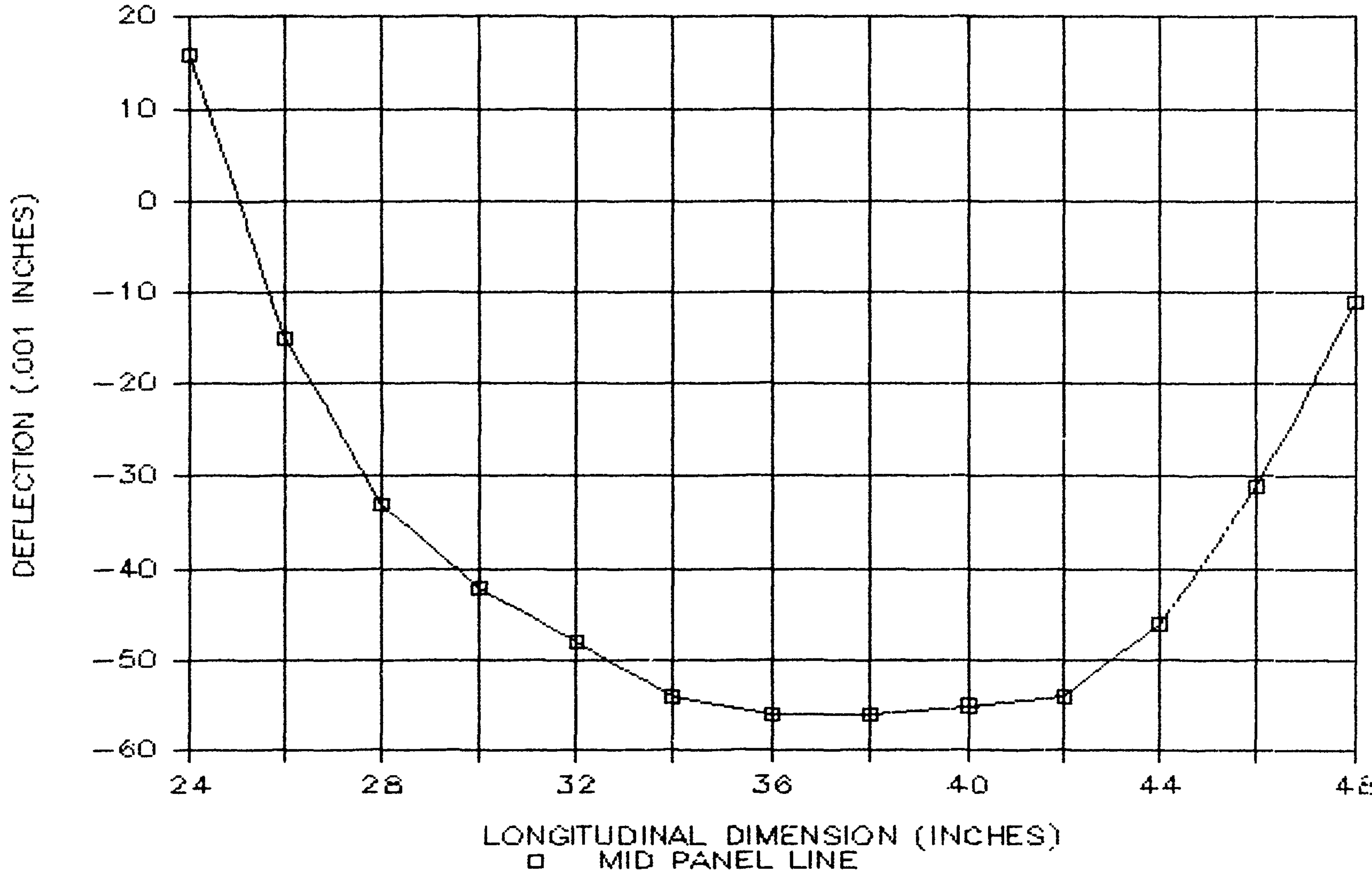
LONGITUDE

F						G	
0	9	17	16	7	4	12	
-4	-10	-11	-15	-15	-8	19	
-5	-21	-29	-33	-28	-12	20	
-4	-25	-39	-42	-34	-13	21	
-4	-28	-44	-48	-38	-15	21	
-5	-33	-49	-54	-42	-16	22	
-4	-33	-52	-56	-45	-18	18	MID PANEL TRANSVERSE LINE
-7	-33	-51	-56	-45	-19	16	
-8	-32	-50	-55	-46	-23	12	
-12	-33	-49	-54	-46	-25	9	
-16	-33	-43	-46	-41	-26	4	
-22	-30	-32	-31	-38	-24	-3	
-23	-23	-17	-11	-8	-13	-16	
J			MID PANEL LONGITUDINAL LINE			K	

Figure 2-26: OUT-OF-PLANE DISTORTION READINGS TAKEN ON PANEL #5 OF THE 3/16" STIFFENED PLATE AFTER WELDING. MEASUREMENTS ARE IN THOUSANDTHS OF AN INCH.

Figure 2-27: 3/16" PLATE

PANEL FIVE AFTER WELDING



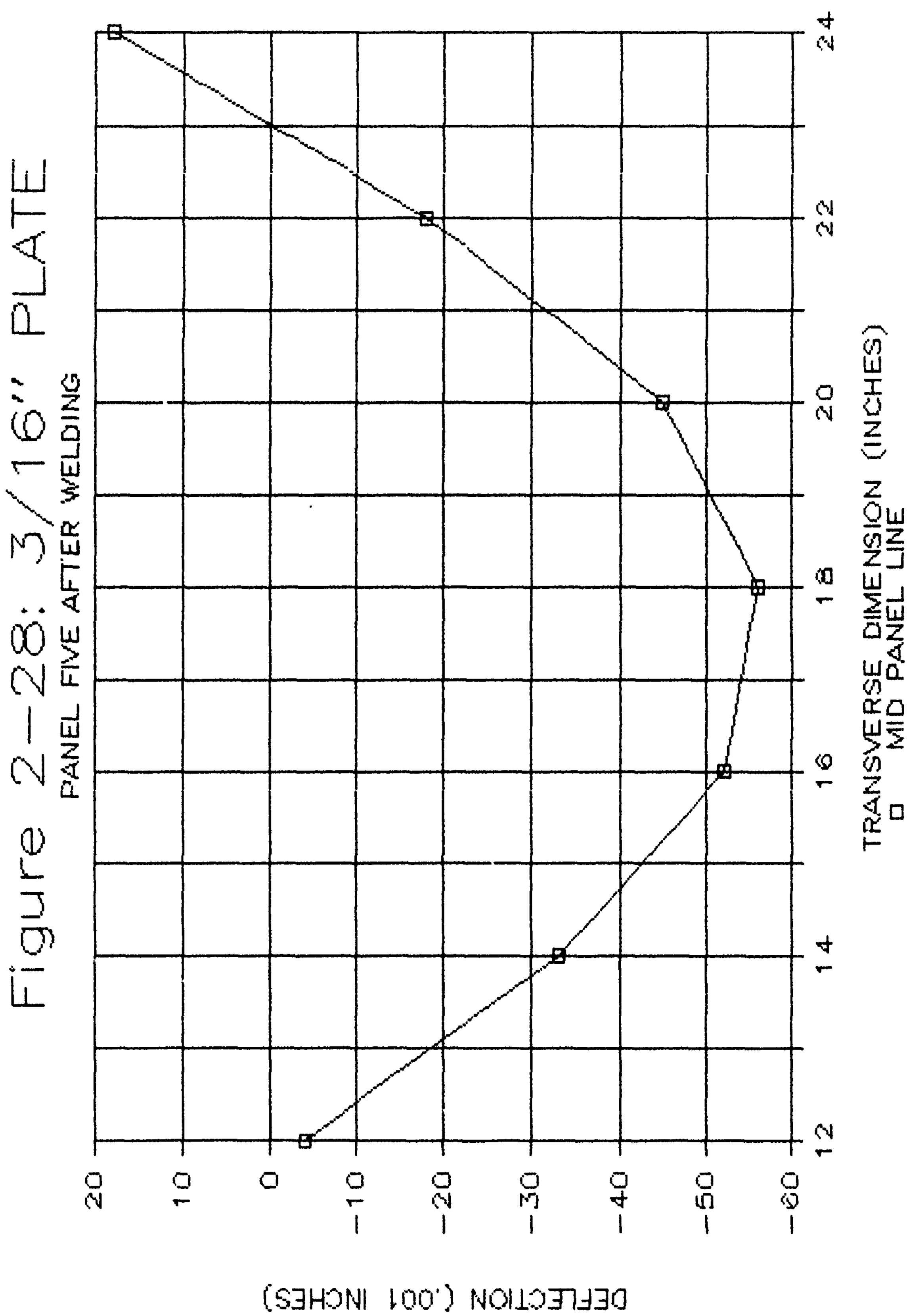


Figure 2-28: 3/16'' PLATE
PANEL FIVE AFTER WELDING
DEFLECTION (.001 INCHES)
20
10
0
-10
-20
-30
-40
-50
-60
12
14
16
18
20
22
24
TRANSVERSE DIMENSION (INCHES)
MID PANEL LINE

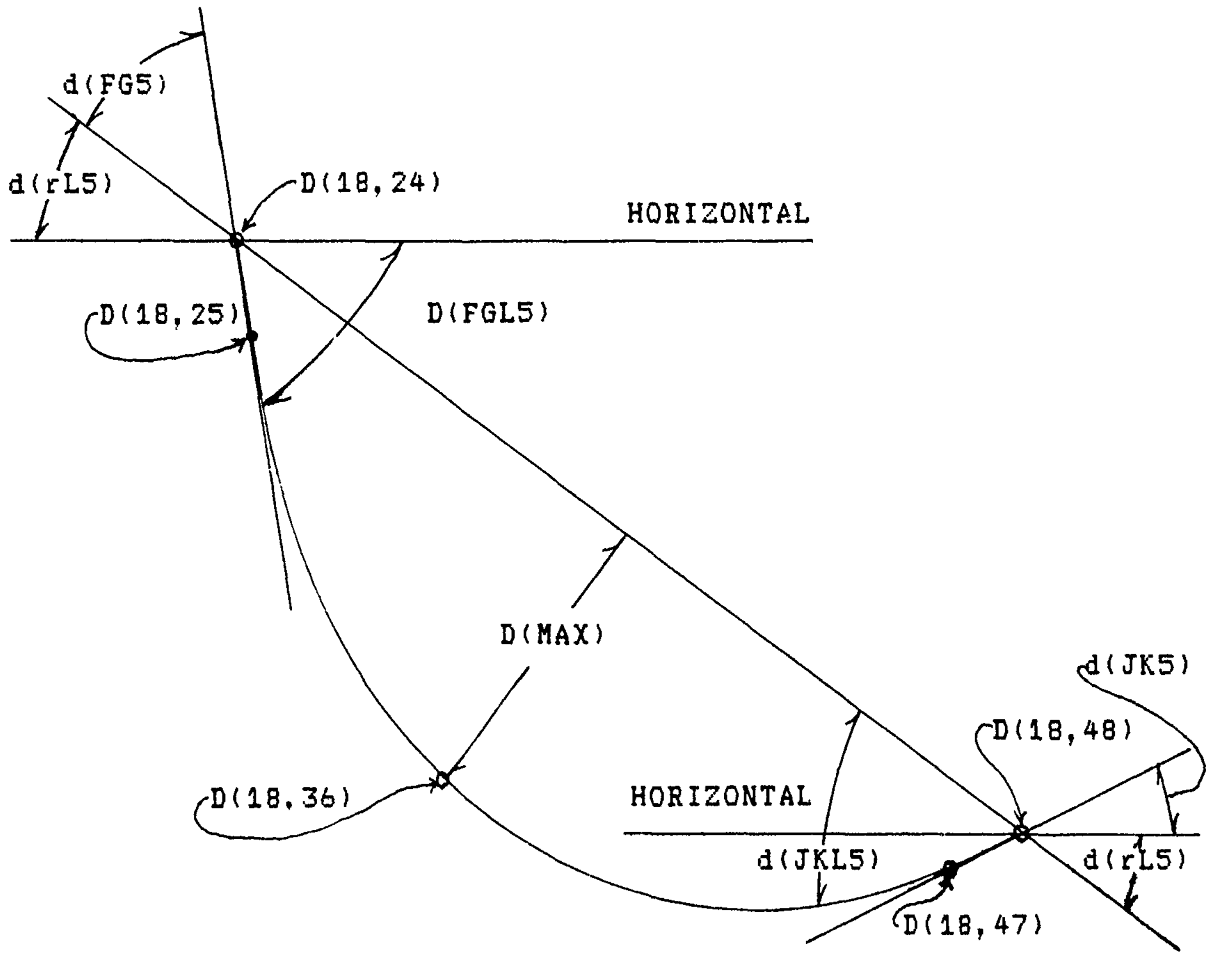


Figure 2-29: ANGLE NOMENCLATURE FOR THE LONGITUDINAL MID-PANEL LINE OF PANEL #5

parentheses, were used for all line heating passes.

For the panel #5 example, the reference angles are

$$d(rL5) = \arctan\{(-.011 - [.016])/24\}$$
$$= -0.001125 \text{ rad}$$

$$d(rt5) = \arctan\{(.018 - [-.004])/12\}$$
$$= 0.001833 \text{ rad}$$

2. Calculate the angular deflection of the mid panel lines at each of the stiffeners, referenced to horizontal (angle d(FGL5) and d(JKL5) in Figure 2-29). The angular deflections for panel #5 are

d(FGL5) = longitudinal angular deflection at stiffener FG on the panel #5 side of the stiffener

$$d(FGL5) = \arctan\{(-.015 - [.016])/2\}$$
$$= -.015499 \text{ rad}$$

d(JKL5) = longitudinal angular deflection at stiffener JK on the panel #5 side of the stiffener

$$d(JKL5) = \arctan\{(.031 - [.011])/2\}$$
$$= .0099997 \text{ rad}$$

d(FJt5) = transverse angular deflection at stiffener FJ on the panel #5 side of the stiffener

$$d(FJt5) = \arctan\{(-.033 - [-.004])/2\}$$
$$= -.014499 \text{ rad}$$

d(GKt5) = transverse angular deflection at stiffener GK on the panel #5 side of the stiffener

$$d(GKt5) = \arctan\{(.018 - [-.018])/2\}$$
$$= .0179981 \text{ rad}$$

The same equations, with appropriate stiffeners designated in parentheses, were used for all line heating passes.

3. Calculate the angular deflection that needs to be

removed at each stiffener, related to the reference angle. Angle d(FG5) and d(JK5) in Figure 2-29. The calculations for these angles are

d(FG5) = angular deflection at mid panel on the panel #5 side of stiffener FG

d(FG5) =ABS{d(FGL5) - d(rL5)}
=ABS{-.015499 - [-.001125]}
= 0.0143738 rad

d(JK5) = angular deflection at mid panel on the panel #5 side of stiffener JK

d(JK5) =ABS{d(JKL5) - d(rL5)}
=ABS{.0099997 - [-.001125]}
= 0.0111247 rad

d(FJ5) = angular deflection at mid panel on the panel #5 side of stiffener FJ

d(FJ5) =ABS{d(FJt5) - d(rt5)}
=ABS{-.014499 - [.001833]}
= -0.01633 rad

d(GK5) = angular deflection at mid panel on the panel #5 side of stiffener GK

d(GK5) =ABS{d(GKt5) - d(rt5)}
=ABS{.0179981 - [.001833]}
= 0.016165 rad

The same equations, with appropriate stiffeners designated in parentheses, are used for all line heating passes.

4. Calculate the velocities that must be used to remove 80 % of the angular deflection. Because of uncertainties in the angular deflection formulas used, only 80% of the angular deflection value calculated was used to determine the line heating velocity. The formula used to calculate the velocities are derived from the d(r1) and d(r2)

curves of Figures 2-17 and 2-18 and are given below.

--Velocity formula for the first line heating pass.

a. [3/16 inch plate]

v(1) = 0.404784/(.8*d(r1) + 0.00633)

b. [1/8 inch plate]

v(1) = 0.184815/(.8*d(r1) + 0.00197)

where, d(r1) and v(1) are the angular deflection that is to be removed and the line heating velocity required, respectively, for the panel and stiffener in question. (For this example, d(r1) = d(FG5) or d(JK5) or d(FJ5) or d(GK5), and v(1) = v(FG5) or v(JK5) or v(FJ5) or v(GK5), depending upon which stiffener is being calculated)

--Velocity formula for the second line heating pass.

c. [3/16 inch plate]

v(2) = 0.3359707/(.8*d(r2) + 0.0052539)

d. [1/8 inch plate]

v(2) = 0.147852/(.8*d(r2) + 0.001576)

where, d(r2) and v(2) are the angular deflection that remains to be removed during the second line heating pass and the line heating velocity required, respectively, for the panel and stiffener in question.

--Velocity formula for the third and fourth line heating pass. (1/8" plate only)

e. v(3) = 0.1182816/(.8*d(r3) + 0.0012608)

f. v(4) = 0.0946258/(.8*d(r4) + 0.0010086)

As an example, to calculate the velocity required, for the first line heating pass, along stiffener FG on the panel #5 side of the 3/16 inch plate; use equation "a" with v(1) = v(FG5) and d(r1) = d(FG5). So:

$$v(FG5) = 0.40784/(.8*0.0143738 + 0.00633)$$
$$= 22.88 \text{ in/min}$$

Tables 2-3 through 2-7 contain the calculated velocities that were applied while heating the panels. These velocities were based on the d(ri) versus v relationship of Figures 2-17 and 2-18.

The results of the investigation are found in Chapter Three and a discussion of these results follows in Chapter Four.

TABLE 2-3: PARAMETERS AND CALCULATED LINE HEATING VELOCITIES USED DURING THE FIRST HEATING PASS ON THE 3/16" STIFFENED PLATE *

HEATING PATH [abi]	REFERENCE ANGLE, d(rci), in rad.	ANGULAR DEFLECTION, d(abci) in rad.	d(abi) in rad.	.8 x d(abi) in rad.	CALCULATED VELOCITY v(abi) in/min	ACTUAL VELOCITY v(act) in/min
FG5	-0.001125	-0.015499	0.0143738	0.011499	22.7	7.7
KJ5	-0.001125	0.009999	0.0111247	0.088998	26.6	9.6
JF5	0.001833	-0.014499	0.0163323	0.013066	20.9	6.9
KG5	0.001833	0.017981	0.016165	0.012932	21.0	7.0
FE4	-0.000083	-0.014999	0.0149155	0.011932	22.2	7.0
JI4	-0.000083	0.013499	0.0135825	0.010866	23.5	8.0
EI4	0.005708	-0.006500	0.0122082	0.009767	25.1	7.4
FJ4	0.005708	0.015749	0.0100404	0.008032	28.2	7.5
CB2	-0.000979	-0.016748	0.0157693	0.012515	21.4	7.6
GF2	-0.000979	0.009499	0.0104789	0.008383	27.5	9.8
FB2	-0.001417	-0.019498	0.0180809	0.014465	19.5	7.0
GC2	-0.001417	0.021997	0.0234131	0.018731	16.2	7.6
JK8	0.002354	-0.008250	0.010604	0.008483	27.3	10.4
NO8	0.002354	0.007999	0.005646	0.004517	37.3	14.6
JN8	-0.001333	-0.017498	0.016165	0.012932	21.0	8.2
KO8	-0.001333	0.012499	0.013833	0.011066	23.3	9.9
GH6	0.00125	-0.016998	0.018248	0.014599	19.3	7.8
KL6	0.00125	0.013999	0.012749	0.010199	24.5	8.8
GK6	0.004333	-0.008750	0.013083	0.010467	24.1	7.7
LH6	0.004333	0.021497	0.017163	0.013731	20.2	7.3
BA1	-0.001542	-0.013499	0.011958	0.009566	25.5	8.2
FE1	-0.001542	0.004	0.005542	0.004433	37.6	14.4
EA1	-0.004166	-0.018498	0.014331	0.011465	22.7	9.0
FB1	-0.004166	0.009499	0.013666	0.010933	23.4	8.7
JI7	0.003417	-0.005	0.008417	0.006733	31.0	13.4
NM7	0.003417	0.012999	0.009583	0.007666	28.9	13.5
IM7	-0.00075	-0.014999	0.014249	0.011399	22.8	12.0
JN7	-0.00075	0.009999	0.010749	0.008599	27.1	12.6
CD3	-0.009499	-0.022996	0.013496	0.010797	23.6	11.9
GH3	-0.009499	-0.002	0.007499	0.005999	32.8	13.7
GC3	0.011333	-0.001	0.012333	0.009866	25.0	12.6
HD3	0.011333	0.025994	0.014661	0.011729	22.4	11.5
KL9	0.003542	-0.005	0.008542	0.006833	30.8	13.6
OP9	0.003542	0.018498	0.014956	0.011965	22.1	11.1
KO9	0.001583	-0.016499	0.018082	0.014466	19.5	11.4
LP9	0.001583	0.019498	0.017914	0.014331	19.6	11.4

* Heating paths are listed by panels and in the sequence by which the panels were line heated.

TABLE 2-4: PARAMETERS AND CALCULATED LINE HEATING VELOCITIES USED DURING THE 2ND HEATING PASS ON THE 3/16" STIFFENED PLATE *

HEATING PATH [abi]	REFERENCE ANGLE, d(rci), in rad.	ANGULAR DEFLECTION, d(abci) in rad.	d(abi) in rad.	.8 x d(abi) in rad.	CALCULATED VELOCITY v(abi) in/min	ACTUAL VELOCITY v(act) in/min
FG5	-0.00075	-0.013499	0.0127492	0.010199	21.7	22.2
KJ5	-0.00075	0.007999	0.0087498	0.069999	27.7	27.7
JF5	0.000417	-0.016499	0.0167152	0.013532	17.9 #	19.2
KG5	0.000417	0.011499	0.0110828	0.008866	23.8	24.3
GH6	-0.001688	-0.017998	0.016311	0.014599	18.4 #	19.7
KL6	-0.001688	0.015748	0.017436	0.013949	17.5 #	19.5
GK6	0.004625	-0.002250	0.006875	0.0055	31.2	31.4
LH6	0.004625	0.019498	0.014873	0.011898	19.6	19.7
CB2	-0.009499	-0.024995	0.0154951	0.012396	19.0	19.8
GF2	-0.009499	-0.001	0.0084997	0.006799	27.9	28.5
FB2	-0.001083	-0.013499	0.0124158	0.009933	22.1	22.2
GC2	-0.001083	0.017998	0.0190814	0.015265	16.4 #	19.8
JK8	0.006625	0.000000	0.006625	0.005300	31.8	32.2
NO8	0.006625	0.007500	0.000875	0.0007	56.4 @	
JN8	-0.001833	-0.005499	0.003667	0.002933	41.0	42.0
KO8	-0.001833	0.0025	0.004333	0.003467	38.5	39.3
BA1	-0.009958	-0.021997	0.012038	0.009631	22.6	23.4
FE1	-0.009958	-0.005750	0.004208	0.003367	39.0	39.2
EA1	-0.004166	-0.015999	0.011832	0.009466	22.8	23.0
FB1	-0.004166	0.0035	0.007666	0.006133	29.5	29.4
CD3	-0.011166	-0.019997	0.008831	0.007065	27.3	28.0
GH3	-0.011166	-0.008999	0.002166	0.001733	48.1	46.7
GC3	0.011666	0.009499	0.002166	0.001733	48.1	46.6
HD3	0.011666	0.021997	0.010330	0.008264	24.9	24.8
JI7	0.006958	0.003	0.003958	0.003166	39.9	40.5
NM7	0.006958	0.010999	0.004041	0.003233	39.6	40.0
IM7	-0.001833	-0.010499	0.008666	0.006933	27.6	27.8
JN7	-0.001833	0.0025	0.004333	0.003467	38.5	39.8
KL9	0.006375	0.005750	0.000625	0.005	58.4 @	
OP9	0.006375	0.018498	0.012123	0.009698	22.5	23.0
KO9	0.001208	-0.006999	0.008208	0.006567	28.4	23.2
LP9	0.001208	0.012999	0.011791	0.009433	22.9	23.0

* Heating paths are listed by panels and in the sequence by which the panels were line heated.

Velocity to slow, therefore used minimum velocity of 19 in/min

@ Velocity to fast. The radiagraph has max speed of 47 in/min. Therefore, this line was not heated.

TABLE 2-5: PARAMETERS AND CALCULATED LINE HEATING VELOCITIES USED DURING THE FIRST HEATING PASS ON THE 1/8" STIFFENED PLATE *

HEATING PATH [abi]	REFERENCE ANGLE, d(rci), in rad.	ANGULAR DEFLECTION, d(abci) in rad.	d(abi) in rad.	.8 x d(abi) in rad.	CALCULATED VELOCITY v(abi) in/min	ACTUAL VELOCITY v(act) in/min
FG5	-0.000958	-0.006500	0.0055416	0.004433	28.9	29.8
KJ5	-0.000958	0.003000	0.0039583	0.003167	36.0	35.8
JF5	0.005375	-0.010750	0.0161245	0.012899	12.4	12.4
KG5	0.005375	0.019498	0.0141226	0.011298	13.9	14.1
FE4	-0.001625	-0.021997	0.0203715	0.016297	10.1	11.3
JI4	-0.001625	0.004000	0.0056250	0.004500	28.6	29.5
EI4	0.008916	0.001000	0.0079164	0.006333	22.3	22.5
FJ4	0.008916	0.013999	0.0050827	0.004066	30.6	31.0
GH6	0.000958	-0.009999	0.010958	0.008766	17.2	17.6
KL6	0.000958	0.006999	0.006042	0.004833	27.1	27.9
GK6	0.004667	0.002	0.002667	0.002133	45.0	45.2
LH6	0.004667	0.008999	0.004333	0.003467	34.0	34.4
CB2	0.005708	0.012999	0.007291	0.005833	23.7	23.6
GF2	0.005708	0.005999	0.0117082	0.009367	16.3	16.5
FB2	0.003167	0.005	0.0018333	0.001467	53.8	47.1
GC2	0.003167	0.005	0.0018333	0.001467	53.8	47.3
JK8	not heated, already over corrected					
NO8	not heated already over corrected					
JN8	0.009958	0.005	0.004958	0.003966	31.1	31.1
KO8	0.009958	0.015249	0.005291	0.004233	29.8	30.4
CD3	0.007521	0.002	0.005521	0.004417	28.9	30.5
GH3	0.007521	0.011500	0.003979	0.003183	35.9	35.5
GC3	0.0005	-0.011500	0.012000	0.009599	16.0	16.4
HD3	0.0005	0.011999	0.011499	0.009200	16.6	16.9
BA1	0.002542	-0.006500	0.009042	0.007233	20.1	20.4
FE1	0.002542	0.018498	0.015956	0.012765	12.6	12.6
EA1	0.004417	-0.018248	0.022665	0.018132	9.2	10.1
FB1	0.004417	0.023746	0.019329	0.015463	10.6	10.3
JI7	-0.005	-0.024745	0.019745	0.015796	10.4	11.8
NM7	-0.005	0.008500	0.013500	0.010800	14.5	14.8
IM7	0.01025	-0.010500	0.020749	0.016599	10.0	11.6
JN7	0.01025	0.031739	0.021490	0.017192	9.7	11.9
KL9	-0.004125	-0.007000	0.002875	0.002300	43.3	44.7
OP9	-0.004125	0.00425	0.008375	0.0067	21.3	21.8
KO9	0.002833	-0.012999	0.015833	0.012666	12.6	12.5
LP9	0.002833	0.015249	0.012416	0.009932	15.5	15.9

* Heating paths are listed by panels and in the sequence by which the panels were line heated.

TABLE 2-6: PARAMETERS AND CALCULATED LINE HEATING VELOCITIES USED DURING THE 2ND HEATING PASS ON THE 1/8" STIFFENED PLATE *

HEATING PATH [abi]	REFERENCE ANGLE, d(rci), in rad.	ANGULAR DEFLECTION, d(abci) in rad.	d(abi) in rad.	.8 x d(abi) in rad.	CALCULATED VELOCITY v(abi) in/min	ACTUAL VELOCITY v(act) in/min
FG5	not heated, already over corrected					
KJ5	not heated, already over corrected					
JF5	0.005583	-0.00375	0.0093333	0.007467	16.4 #	18.9
KG5	0.005583	0.017498	0.0119149	0.009532	13.3 #	19.0
FE4	not heated, already over corrected					
JI4	not heated, already over corrected					
EI4	0.014666	0.002	0.0126656	0.010133	12.6 #	18.2
FJ4	0.014666	0.005500	0.0091657	0.007333	16.6 #	19.6
BA1	0.0005	-0.006000	0.006500	0.005200	21.8	19.0
FE1	0.0005	0.013999	0.013499	0.010800	12.0 #	19.1
EA1	0.003958	-0.025245	0.029203	0.023362	5.9 #	20.1
FB1	0.003958	0.026993	0.023053	0.018443	7.4 #	19.6
JI7	-0.002792	-0.023995	0.021204	0.016963	8.0 #	19.2
NM7	-0.002792	0.014999	0.017791	0.014232	9.4 #	19.5
IM7	0.006833	-0.018496	0.025331	0.020265	6.8 #	19.2
JN7	0.006833	0.033737	0.026904	0.021523	6.4 #	19.0

* Heating paths are listed by panels and in the sequence by which the panels were line heated.

\# Velocity to slow, therefore used a minimum velocity of 19 in/min.

TABLE 2-7: PARAMETERS AND CALCULATED LINE HEATING VELOCITIES USED DURING THE 3RD AND 4TH HEATING PASS ON THE 1/8" STIFFENED PLATE *

HEATING PATH [abi]	REFERENCE ANGLE. d(rci). in rad.	ANGULAR DEFLECTION. d(abci) in rad.	d(abi) in rad.	.8 x d(abi) in rad.	CALCULATED VELOCITY v(abi) in/min	ACTUAL VELOCITY v(act) in/min
			3RD PASS			
BA1	0.000438	-0.00625	0.006688	0.00535	17.9 #	19.1
FE1	0.000438	0.00575	0.005313	0.00425	21.5	18.9
EA1	0.004	-0.021	0.025	0.02	5.6 #	19.0
FB1	0.004	0.02125	0.01725	0.0138	7.9 #	19.0
JI7	-0.00275	-0.015	0.01225	0.0098	10.7 #	19.1
NM7	-0.00275	0.0035	0.00625	0.005	18.9	19.1
IM7	0.006667	-0.0175	0.024167	0.019333	5.7 #	19.1
JN7	0.006667	0.031	0.024333	0.019467	5.7 #	19.2
			4TH PASS			
JI7	-0.0025	-0.007	0.0045	0.011167	17.2 #	19.1
NM7	-0.0025	0.005	0.0075	0.006	13.5	19.2
IM7	0.006333	-0.01325	0.019583	0.015667	5.7 #	19.2
JN7	0.006333	0.0255	0.019167	0.015333	5.7 #	19.2
BA1	0.000438	-0.00625	0.006688	0.00535	14.9 #	18.8
FE1	0.000438	0.00542	0.004979	0.003983	19.0	18.9
EA1	0.00375	-0.014	0.01775	0.0142	6.2 #	18.8
FB1	0.00375	0.01575	0.012	0.0096	8.9 #	19.0

* Heating paths are listed by panels and in the sequence by which the panels were line heated. It was assumed that angular distortion removal effectiveness decreased by the same % on the 3rd and 4th pass as it did on the 2nd pass (i.e. 80%).

\# Velocity to slow, therefore used a minimum velocity of 19 in/min.

CHAPTER THREE

RESULTS

The results of experiments on the free-end samples and the stiffened plates are in the form of tables and graphs. Tables 3-1 through 3-9 and Appendixes C through Y contain this data. They are discussed below.

3.1 Presentation of Free-end Sample Data

Appendix C contains Tables of data obtained from the free-end samples. The method of obtaining and the use of this data was discussed in sections 2.3.2 and 2.4.1. Section I contains the data for the 3/16" thick samples and section II contains the data for the 1/8" samples. Figures 2-17 and 2-18 were plotted using the d(ri) and 1/vi data obtained from sections B and C of this appendix.

3.2 Presentation of Stiffened Plate Data

Appendixes D, E, F, and G contain the out-of-plane deflection readings for the stiffened plates. Appendix D contains deflection data for the 3/16" plate recorded after welding and after each panel was line heated the first time. The first six sets of data contain deflection measurements recorded at each 2 inch increment from point A to point P, see Figure 2-21. All other sets of data, in Appendix D and all data in Appendixes E, F, and G, contain recorded deflections on stiffeners and mid-panel lines only. Refer to the discussion in section 2.4.2 and Figure 2-22.

Appendix E contains deflection data for the 3/16" plate recorded after each panel was line heated the second time.

Appendix F contains deflection data for the 1/8" plate recorded after welding and after each panel was line heated the first time.

Appendix G contains deflection data for the 1/8" plate recorded after panels 5, 4, 1, and 7 were line heated a second time and after panels 1 and 7 were line heated for a third and fourth time.

In appendixes D, E, F, and G the TRANSVERSE and LONGITUDE spacing was 2 inches. All deflection readings in the matrixes are in thousandths (0.001) of an inches. For example, the out-of-plane distortion at 10 inches TRANSVERSE and 2 inches LONGITUDE, in the matrix labeled "DISTORTION MEASUREMENTS OF 3/16" PLATE AFTER WELDING", is -0.075 inches (i.e. 0.075 below the reference point). This point is designated D(6,2), in the nomenclature, as it is on the 6th line in the TRANSVERSE direction and the 2nd line in the LONGITUDE direction.

3.2.1 Graphs of Mid-Panel deflections

Appendixes H, I, J, K, and L are graphs of the mid-panel deflection data recorded in Appendixes D, E, F, AND G discussed above. Each appendix has the graphs arranged in the following sequence:

A. Transverse Mid-Panel Deflections

1. Panels 1, 2, and 3
2. Panels 4, 5, and 6
3. Panels 7, 8, and 9

B. Longitudinal mid-panel deflections

1. Panels 1, 4, and 7
2. Panels 2, 5, and 8
3. Panels 3, 6, and 9

Each set of graphs contains up to six plots of mid-panel deflection measurements, presented in the order at which each panel was line heated and measured. For example, the set of graphs titled "3/16" PLATE DEFLECTION" for "PANELS ONE, TWO, AND THREE" contains plots of mid-panel deflection measurements of the 3/16" plate for:

1. after welding
2. after line heating panel 5
3. after line heating panel 4
4. after line heating panel 2
5. after line heating panel 8
6. after line heating panel 6

The set of graphs on the following page contains plots of mid-panel deflection measurements for:

1. after line heating panel 1
2. after line heating panel 7
3. after line heating panel 3
4. after line heating panel 9

These plots are in the order at which the panels were line heated as discussed in section 2.4.3 and listed in Tables 2-1 and 2-2.

Appendix H contains the graphs of out-of-plane deflection readings on the 3/16" plate for after welding and after the

first line heating pass of each panel.

Appendix I contains the graphs of deflection readings after the second pass on the 3/16" plate.

Appendix J, K, and L contains the graphs of deflection readings for the 1/8" plate after the first pass, second pass, and third and fourth pass, respectively.

3.2.2 Actual Angular Distortion Removed from Plates

Figures 2-17 and 2-18 show the angular distortion versus velocity relationship that was used while heating the stiffened plates. This relationship was experimentally determined using the free-end samples, as discussed in sections 2.3.2 and 2.4.1. The actual angular distortion versus velocity relationship for each stiffened plate was determined by measuring the angular distortion in each panel prior to and after each panel was line heated. Tables 3-1 through 3-5 give these measured distortions and the actual angular distortions that were removed after heating a panel. The negative values in the last column indicate that angular distortion was increased after heating at that stiffener. Figures 4-1 through 4-6 were graphed using the data from these tables.

3.2.3 Shape of Panel Distortion

Appendixes M, N, O, P, Q, R, S, T, and U contain plots of graphs obtained from the first 6 sets of deflection data points found in Appendix D. These are the sets of deflection readings that contained measurements recorded at every 2 inch

TABLE 3-1: ACTUAL ANGULAR DISTORTION REMOVED FROM THE 3/16" STIFFENED PLATE DURING THE FIRST HEATING PASS *

HEATING PATH [abi]	PRE-HEATING ANGULAR DIST. d(abci)pre in rad.	POST-HEATING ANGULAR DIST. d(abci)post in rad.	ACTUAL VELOCITY v(abi) in/min	ACTUAL ANGULAR DIST. REMOVED d(ri)act in rad.
FG5	-0.0155	-0.0075	7.7	0.008
KJ5	0.0100	0.0055	9.6	0.0045
JF5	-0.0145	-0.0103	6.9	0.0042
KG5	0.0180	0.0118	7.0	0.0062
FE4	-0.0150	-0.023	7.0	-0.008
JI4	0.0135	0.02	8.0	-0.0065
EI4	-0.0065	0.008	7.4	0.0145
FJ4	0.0157	-0.011	7.5	0.0267
CB2	-0.0167	-0.018	7.6	-0.0013
GF2	0.0095	0.0065	9.8	0.003
FB2	-0.0195	-0.019	7.0	0.0005
GC2	0.0220	0.0155	7.6	0.0065
JK8	-0.0083	-0.0005	10.4	0.0078
NO8	0.0080	0.0045	14.6	0.0035
JN8	-0.0175	-0.008	8.2	0.0095
KO8	0.0125	0.0025	9.9	0.010
GH6	-0.0170	-0.011	7.8	0.006
KL6	0.0140	0.0245	8.8	-0.0105
GK6	-0.0088	-0.005	7.7	0.0038
LH6	0.0215	0.0195	7.3	0.002
BA1	-0.0135	-0.0225	8.2	-0.009
FE1	0.0040	-0.0088	14.4	0.0128
EA1	-0.0185	-0.015	9.0	0.0035
FB1	0.0095	0.0053	8.7	0.0042
JI7	-0.005	0.0025	13.4	0.0075
NM7	0.0130	0.009	13.5	0.004
IM7	-0.0150	-0.010	12.0	0.005
JN7	0.0100	0.0025	12.6	0.0075
CD3	-0.0230	-0.0195	11.9	0.0035
GH3	-0.0020	-0.0055	13.7	0.0035
GC3	-0.0010	0.0055	12.6	0.0065
HD3	0.0260	0.0203	11.5	0.0057
KL9	-0.005	0.0038	13.6	0.0088
OP9	0.0185	0.015	11.1	0.0035
KO9	-0.0165	-0.0078	11.4	0.0087
LP9	0.0195	0.0135	11.4	0.006

* Heating paths are listed by panels and in the sequence by which the panels were line heated.

TABLE 3-2: ACTUAL ANGULAR DISTORTION REMOVED FROM THE 3/16" STIFFENED PLATE DURING THE SECOND HEATING PASS *

HEATING PATH [abi]	PRE-HEATING ANGULAR DIST. d(abci)pre in rad.	POST-HEATING ANGULAR DIST. d(abci)post in rad.	ACTUAL VELOCITY v(abi) in/min	ACTUAL ANGULAR DIST. REMOVED d(ri)act in rad.
FG5	-0.0135	-0.0023	22.2	0.0112
KJ5	0.0080	0.0000	27.7	0.008
JF5	-0.0165	-0.011	19.2	0.0055
KG5	0.0115	0.0068	24.3	0.0047
GH6	-0.0180	-0.0093	19.7	0.0087
KL6	0.0157	0.0103	19.5	0.0054
GK6	-0.0023	0.0025	31.4	0.0048
LH6	0.0195	0.014	19.7	0.0055
CB2	-0.0250	-0.016	19.8	0.009
GF2	0.001	-0.007	28.5	0.008
FB2	-0.0135	-0.0045	22.2	0.009
GC2	0.0180	0.0085	19.8	0.0095
JK8	0.0000	0.009	32.2	0.009
NO8	0.0075	0.0055	----	0.002
JN8	-0.0055	-0.0008	42.0	0.0047
KO8	0.0025	-0.0025	39.3	0.005
BA1	-0.0220	-0.011	23.4	0.011
FE1	-0.0058	-0.0118	39.2	0.006
EA1	-0.0160	-0.0065	23.0	0.0095
FB1	0.0035	-0.006	29.4	0.0095
CD3	-0.0200	-0.0138	28.0	0.0062
GH3	-0.0090	-0.0133	46.7	0.0043
GC3	0.0095	0.0145	46.6	0.005
HD3	0.0220	0.015	24.8	0.007
JI7	0.003	0.0075	40.5	0.0045
NM7	0.0110	0.0075	40.0	0.0035
IM7	-0.0105	-0.0065	27.8	0.004
JN7	0.0025	-0.0023	39.8	0.0048
KL9	0.0058	0.01	----	0.0042
OP9	0.0185	0.0083	23.0	0.0102
KO9	-0.0070	0.0045	23.2	0.0115
LP9	0.0130	0.004	23.0	0.009

* Heating paths are listed by panels and in the sequence by which the panels were line heated.

TABLE 3-3: ACTUAL ANGULAR DISTORTION REMOVED FROM THE 1/8" STIFFENED PLATE DURING THE FIRST HEATING PASS *

HEATING PATH [abi]	PRE-HEATING ANGULAR DIST. d(abci)pre in rad.	POST-HEATING ANGULAR DIST. d(abci)post in rad.	ACTUAL VELOCITY v(abi) in/min	ACTUAL ANGULAR DIST. REMOVED d(ri)act in rad.
FG5	-0.0065	0.0018	29.8	0.0083
KJ5	0.0030	-0.006	35.8	0.009
JF5	-0.0108	0.0005	12.4	0.0113
KG5	0.0195	0.012	14.1	0.0075
FE4	-0.0220	-0.0163	11.3	0.0057
JI4	0.0040	-0.0013	29.5	0.0053
EI4	0.0010	0.0035	22.5	0.0025
FJ4	0.0140	0.013	31.0	0.001
GH6	-0.0100	-0.003	17.6	0.007
KL6	0.0070	0.0048	27.9	0.0022
GK6	0.0020	0.002	45.2	0.0000
LH6	0.0090	0.009	34.4	0.0000
CB2	0.0130	0.0160	23.6	0.003
GF2	0.0060	-0.014	16.5	0.02
FB2	0.005	0.007	47.1	0.002
GC2	0.005	0.003	47.3	0.002
JK8	0.0045	0.0075	----	0.003
NO8	-0.009	-0.0125	----	0.0035
JN8	0.005	0.0123	31.1	0.0073
KO8	0.0153	0.009	30.4	0.0063
CD3	0.002	0.0073	30.5	0.0053
GH3	0.0115	0.005	35.5	0.0065
GC3	-0.0115	0.0023	16.4	0.0138
HD3	0.0120	0.0035	16.9	0.0085
BA1	-0.0065	-0.0055	20.4	0.001
FE1	0.0185	0.0125	12.6	0.006
EA1	-0.0182	-0.0245	10.1	-0.0063
FB1	0.0237	0.026	10.3	-0.0023
JI7	-0.0247	-0.0225	11.8	0.0022
NM7	0.0085	0.0075	14.8	0.001
IM7	-0.0105	-0.018	11.6	-0.0075
JN7	0.0317	0.035	11.9	-0.0033
KL9	-0.0070	-0.0005	44.7	0.0065
OP9	0.0043	-0.0003	21.8	0.0046
KO9	-0.0130	-0.006	12.5	0.007
LP9	0.0152	0.012	15.9	0.0032

* Heating paths are listed by panels and in the sequence by which the panels were line heated.

TABLE 3-4: ACTUAL ANGULAR DISTORTION REMOVED FROM THE 1/8" STIFFENED PLATE DURING THE SECOND HEATING PASS *

HEATING PATH [abi]	PRE-HEATING ANGULAR DIST. d(abci)pre in rad.	POST-HEATING ANGULAR DIST. d(abci)post in rad.	ACTUAL VELOCITY v(abi) in/min	ACTUAL ANGULAR DIST. REMOVED d(ri)act in rad.
FG5	0.001	0.0098	----	0.0088
KJ5	-0.007	-0.0095	----	0.0025
JF5	0.0038	0.0213	18.9	0.0251
KG5	0.0175	-0.0005	19.0	0.018
FE4	-0.0145	-0.013	----	0.0015
JI4	0.001	-0.0018	----	0.0028
EI4	0.002	0.0063	18.2	0.0043
FJ4	0.0055	0.0025	19.6	0.003
BA1	-0.0060	-0.0015	19.0	0.0045
FE1	0.0140	0.003	19.1	0.011
EA1	-0.0252	-0.0205	20.1	0.0047
FB1	0.0270	0.021	19.6	0.006
JI7	-0.0240	-0.015	19.2	0.009
NM7	0.0150	0.0035	19.5	0.0115
IM7	-0.0185	-0.0175	19.2	0.001
JN7	0.0337	0.031	19.0	0.0027

* Heating paths are listed by panels and in the sequence by which the panels were line heated.

TABLE 3-5: ACTUAL ANGULAR DISTORTION REMOVED FROM THE 1/8" STIFFENED PLATE DURING THE 3RD AND 4TH HEATING PASS *

HEATING PATH [abi]	PRE-HEATING ANGULAR DIST. d(abci)pre in rad.	POST-HEATING ANGULAR DIST. d(abci)post in rad.	ACTUAL VELOCITY v(abi) in/min	ACTUAL ANGULAR DIST. REMOVED d(ri)act in rad.
		3RD PASS		
BA1	-0.0063	0.0013	19.1	0.0076
FE1	0.0058	-0.0035	18.9	0.0093
EA1	-0.021	-0.0014	19.0	0.0196
FB1	0.0213	0.0103	19.0	0.011
JI7	-0.015	-0.007	19.1	0.008
NM7	0.0035	0.001	19.1	0.0025
IM7	-0.0175	-0.0133	19.1	0.0042
JN7	0.031	0.0255	19.2	0.0055
		4TH PASS		
JI7	-0.007	-0.0013	19.1	0.0057
NM7	0.005	-0.0025	19.2	0.0075
IM7	-0.0133	-0.0083	19.2	0.005
JN7	0.0255	0.0198	19.2	0.0057
BA1	-0.0063	0.0035	18.8	0.0098
FE1	0.0054	-0.0085	18.9	0.0139
EA1	-0.014	-0.0045	18.8	0.0095
FB1	0.0158	0.007	19.0	0.0088

* Heating paths are listed by panels and in the sequence by which the panels were line heated.

spacing on the plates from point A to point P. Appendixes M through U are compared in Chapter 4 with results from previous investigations at M.I.T. These graphs show the change in deflection along each of the transverse and longitudinal lines, of the 3/16" plate, as panels 5, 4, 2, 8, and 6 are line heated. Refer to Figure 3-1 during the following discussion.

Appendix M contains the plates transverse out-of-plane deflection readings for lines AD2 through AD7. The First set of graphs titled "3/16" PLATE DEFLECTION" is the after welding data. The second set of graphs is the data taken after panel 5 was line heated; the third set after panel 4 was line heated; and so forth.

Appendix N contains the plates transverse out-of-plane deflection readings for lines AD7 through AD12.

Appendixes O and P contain the plates transverse out-of-plane deflection readings for lines EH2 through EH12.

Appendixes Q and R contain the transverse deflection readings for lines IL2 through IL12.

Appendixes S, T, and U contain the longitudinal out-of-plane deflection readings for lines AM2 through AM6, BN2 through BN6 and CO2 through CO6, respectively.

3.2.4 Mid-Panel Deflections D(MAX)iT and D(MAX)iL

Appendixes V and W contain tables of mid-panel deflections, D(MAX)iT and D(MAX)iL, for the stiffened plates after welding and after each panel was line heated the given number of times. Refer to Figure 3-2 for a pictorial

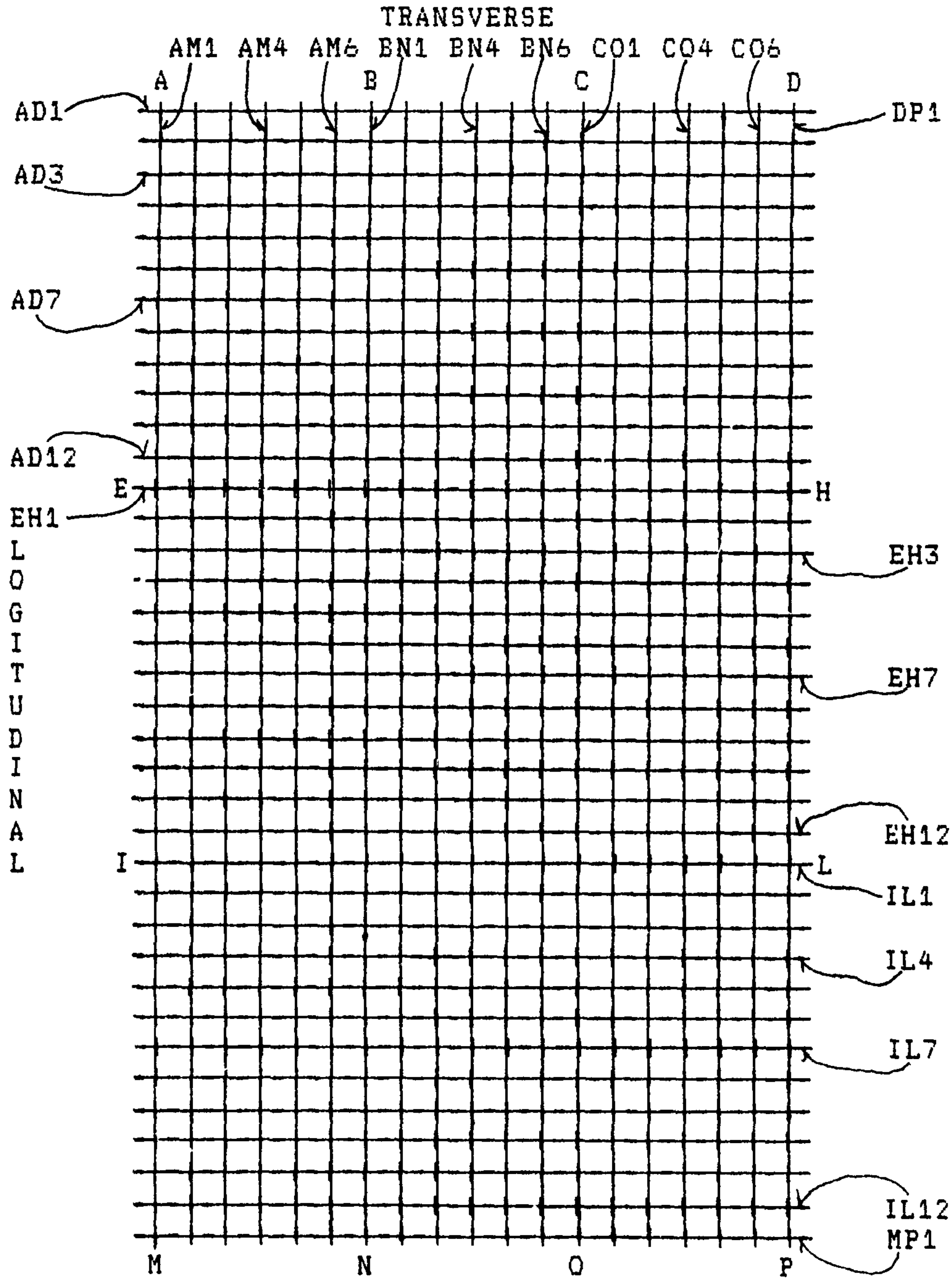


Figure 3-1: PICTORIAL DEFINITION OF THE LINE NOMENCLATURE USED IN APPENDIXES M THROUGH U.

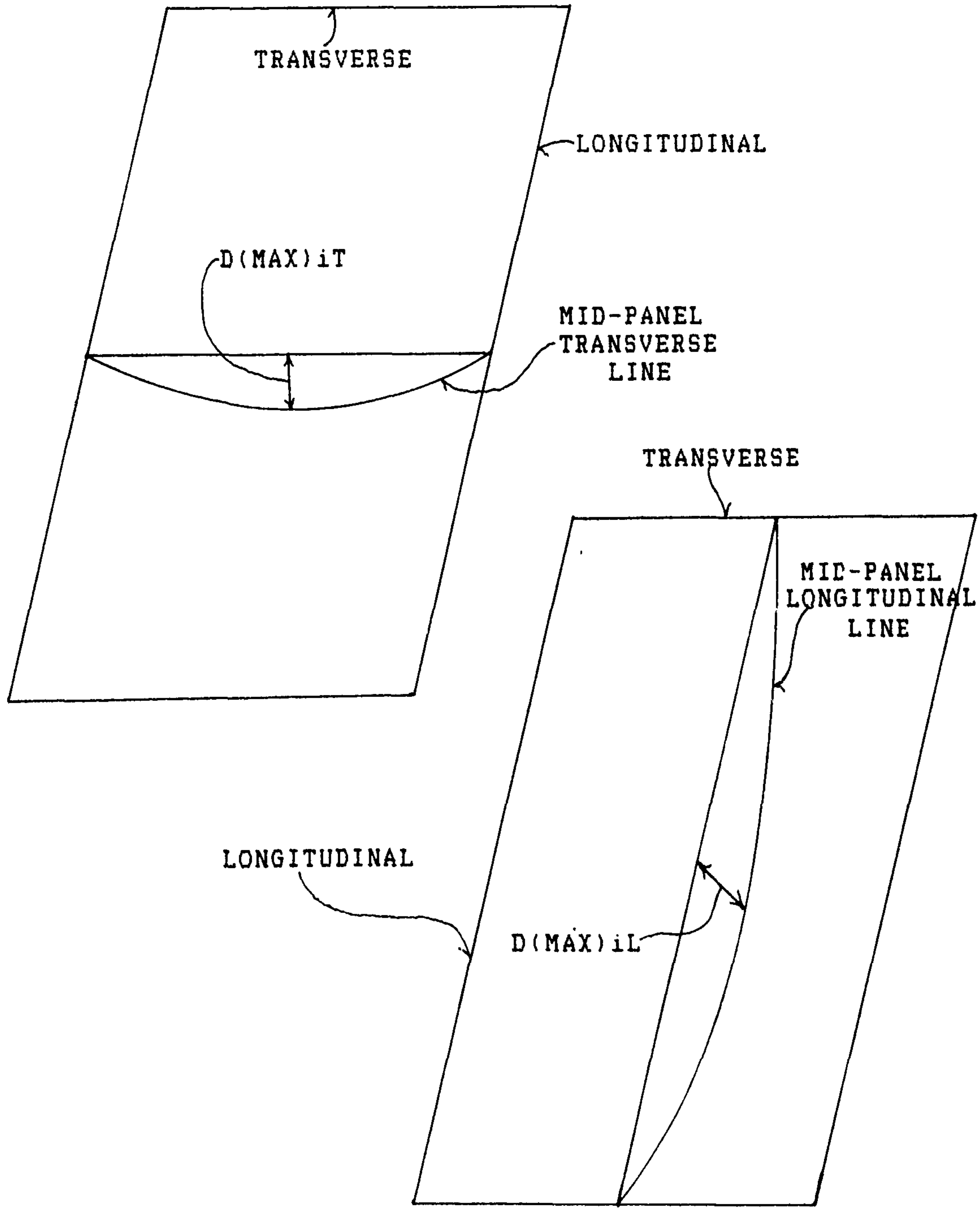


Figure 3-2: PICTORIAL DEFINITION OF D(MAX)iT AND D(MAX)iL

definition of D(MAX)iT and D(MAX)iL.

Appendix V contains the mid-panel deflection data, D(MAX)iT and D(MAX)iL, for the 3/16" plate:

1. after welding,
2. after each panel was line heated the first time, and
3. after each panel was line heated the second time.

Appendix W contains the mid-panel deflection data, D(MAX)iT and D(MAX)iL, for the 1/8" plate:

1. after welding,
2. after each panel was line heated the first time,
3. after panels 5, 4, 1, and 7 were line heated the second time,
4. after panels 1 and 7 were line heated the third time, and
5. after panels 7 and 1 were line heated the fourth time.

The data contained in Appendixes V and W was used to calculate the entries in Tables 3-6 through 3-9. These tables provide the reader with the amount of mid-panel out-of-plane distortion, D(MAX)iT and D(MAX)iL, that was removed from each panel after that panel was line heated and the overall accumulative affect from heating all panels during that heating pass. For example, the "Change in D(MAX)3T" of the 3/16" plate after heating panel #3 the first time was 0.0215 inches; while the overall "Change in D(MAX)3T" after all the panels of the 3/16" plate were heated the first time was 0.029 inches. See Table 3-6.

Appendixes X and Y contain tables comparing the effect of line heating on D(MAX)iT and D(MAX)iL. Appendix X is for the

TABLE 3-6: REDUCTION OF D(MAX)iT IN THE 3/16" PLATE

The amount of reduction in D(MAX)iT produced in each panel immediately after that panel was line heated and the overall reduction in D(MAX)iT of each panel after all panels were line heated.

	CHANGE IN D(MAX)1T	CHANGE IN D(MAX)2T	CHANGE IN D(MAX)3T	CHANGE IN D(MAX)4T	CHANGE IN D(MAX)5T	CHANGE IN D(MAX)6T	CHANGE IN D(MAX)7T	CHANGE IN D(MAX)8T	CHANGE IN D(MAX)9T
FIRST PASS	Reduction in D(MAX)iT caused by heating panel #i								
	0.0145	0.026	0.0215	0.1023	0.0298	0.0015	0.022	0.0415	0.0298
	The overall reduction in D(MAX)iT of each panel after all panels were heated								
	0.023	0.01	0.029	0.1115	0.0115	0.0165	0.0355	0.033	0.0368
SECOND PASS	Reduction in D(MAX)iT caused by heating panel #i								
	0.0405	0.0395	0.0275	----	0.0183	0.0253	0.0195	0.0245	0.0433
	The overall reduction in D(MAX)iT of each panel after all panels were heated								
	0.0425	0.034	0.034	0.0125	0.012	0.0315	0.0175	0.024	0.0443

TABLE 3-7: REDUCTION OF D(MAX)iL IN THE 3/16" PLATE

The amount of reduction in D(MAX)iL produced in each panel immediately after that panel was line heated and the overall reduction in D(MAX)iL of each panel after all panels were line heated.

	CHANGE IN D(MAX)1L	CHANGE IN D(MAX)2L	CHANGE IN D(MAX)3L	CHANGE IN D(MAX)4L	CHANGE IN D(MAX)5L	CHANGE IN D(MAX)6L	CHANGE IN D(MAX)7L	CHANGE IN D(MAX)8L	CHANGE IN D(MAX)9L
FIRST PASS	Reduction in D(MAX)iL caused by heating panel #i								
	0.0018	0.0323	0.014	0.072	0.026	-0.0095	0.015	0.0425	0.0228
	The overall reduction in D(MAX)iL of each panel after all panels were heated								
	0.005	0.004	0.012	0.082	-0.0075	-0.0048	0.022	0.022	0.0223
SECOND PASS	Reduction in D(MAX)iL caused by heating panel #i								
	0.0405	0.0395	0.0265	---	0.0158	0.0233	0.0195	0.0235	0.0426
	The overall reduction in D(MAX)iL of each panel after all panels were heated								
	0.0405	0.034	0.033	0.009	0.0095	0.0293	0.018	0.0255	0.0431

TABLE 3-8: REDUCTION OF D(MAX)iT IN THE 1/8" PLATE

The amount of reduction in D(MAX)iT produced in each panel immediately after that panel was line heated and the overall reduction in D(MAX)iT of each panel after all panels were heated.

		CHANGE IN D(MAX)1T	CHANGE IN D(MAX)2T	CHANGE IN D(MAX)3T	CHANGE IN D(MAX)4T	CHANGE IN D(MAX)5T	CHANGE IN D(MAX)6T	CHANGE IN D(MAX)7T	CHANGE IN D(MAX)8T	CHANGE IN D(MAX)9T
FIRST PASS	Reduction in D(MAX)iT caused by heating panel #i	-0.033	0.0095	0.049	0.0035	0.0453	-0.001	-0.033	0.0278	0.015
	The overall reduction in D(MAX)iT of each panel after all panels were heated	-0.058	0.0255	0.038	0.018	0.0173	0.023	-0.037	0.0495	0.0095
SECOND PASS	Reduction in D(MAX)iT caused by heating panel #i	0.0213	---	---	0.0278	0.1045	---	0.01	---	---
	The overall reduction in D(MAX)iT of each panel after all panels were heated	0.0195	0.0015	0.0038	0.0258	0.105	0.0075	0.008	-0.017	0.1145 DAMAGED
3RD PASS	Reduction in D(MAX)iT caused by heating panel #i	0.0408	---	---	---	---	---	0.0203	---	---
	The overall reduction in D(MAX)iT of each panel after all panels were heated	0.0408	0.0035	-0.0013	-0.0015	0.0055	-0.0013	0.0205	-0.0015	0
4TH PASS	Reduction in D(MAX)iT caused by heating panel #i	0.0428	---	---	---	---	---	0.0258	---	---
	The overall reduction in D(MAX)iT of each panel after all panels were heated	0.0428	0	---	0.0001	0.0015	---	0.0258	-0.0013	---

TABLE 3-9: REDUCTION OF D(MAX)iL IN THE 1/8" PLATE

The amount of reduction in D(MAX)iL produced in each panel immediately after that panel was line heated and the overall reduction in D(MAX)iL of each panel after all panels were heated.

	CHANGE IN D(MAX)1L	CHANGE IN D(MAX)2L	CHANGE IN D(MAX)3L	CHANGE IN D(MAX)4L	CHANGE IN D(MAX)5L	CHANGE IN D(MAX)6L	CHANGE IN D(MAX)7L	CHANGE IN D(MAX)8L	CHANGE IN D(MAX)9L
FIRST PASS			Reduction in D(MAX)iL caused by heating panel #i						
	-0.042	0.0095	0.0465	-0.0003	0.043	-0.003	-0.0393	0.0275	0.011
	The overall reduction in D(MAX)iL of each panel after all panels were heated								
	-0.0713	0.0213	0.034	0.0148	0.0115	0.02	-0.045	0.0455	0.0048
SECOND PASS			Reduction in D(MAX)iL caused by heating panel #i						
	0.0195	---	---	0.0268	0.1055	---	0.0095	---	---
	The overall reduction in D(MAX)iL of each panel after all panels were heated								
	0.0198	0.0018	0.004	0.024	0.105	0.0075	0.0085	-0.017	0.1155 DAMAGED
3RD PASS			Reduction in D(MAX)iL caused by heating panel #i						
	0.0395	---	---	---	---	---	0.0195	---	---
	The overall reduction in D(MAX)iL of each panel after all panels were heated								
	0.0405	0.0035	-0.001	-0.0023	0.005	-0.0013	0.0195	-0.0035	-0.0005
4TH PASS			Reduction in D(MAX)iL caused by heating panel #i						
	0.0418	---	---	---	---	---	0.026	---	---
	The overall reduction in D(MAX)iL of each panel after all panels were heated								
	0.0418	-0.0015	---	0.0015	0.001	---	0.026	---	-0.0003

3/16" stiffened plate and Appendix Y is for the 1/8" plate.

There are two types of comparisons:

1. the affect on D(MAX)iT and D(MAX)iL of line heating each of the panels, and

2. the affect on D(MAX) of all other panels when heating just one panel.

For example, to see the affect that heating all panels has on panel #1 mid-panel transverse deflection, D(MAX)1T, turn to the first set of tables in Appendix X. Under A.1.Transverse we find:

-line heating panel #1 resulted in a reduction of 14.5 thousandths of an inch in D(MAX)1T,

-line heating panel #2 resulted in a reduction in D(MAX)1T of 0.013 inches,

-line heating panel #3 resulted in an increase in D(MAX)1T of 0.001 inches,

-line heating panel #4 resulted in a decrease in D(MAX)1T of 0.00375 inches,

-etc.

To see the affect that line heating panel #1 had on the mid-panel longitudinal deflections of all other panels, turn to the first set of tables in Appendix X. Under A.2.Longitudinal we find:

-D(MAX)1L was reduced by 0.00175 inches,

-D(MAX)2L was reduced by 0.00325 inches,

-D(MAX)3L was increased by 0.003 inches,

-D(MAX)4L was reduced by 0.0103 inches,

-D(MAX)5L was increased by 0.006 inches, etc.

Chapter Four contains the discussion of the results presented in this chapter.

CHAPTER FOUR

DISCUSSION OF RESULTS

Chapter Four contains the discussion of the results presented in Chapter Three.

4.1 Actual Angular Distortion Removal of Stiffened Plates

Figure 4-1 shows the actual angular distortion removed versus inverse flame velocity for the first pass on the 3/16" stiffened plate. Although there is much data scatter, it appears that angular distortion removed decreases as velocity decreases or 1/v increases (i.e. higher energy input) as indicated by the line in Figure 4-1. Note that the majority of the data points fall within the range of 0.002 to 0.008 radians. This is approximately 6 to 24 % of the angular distortion removed at the same velocities in Figure 2-17 and is expected since the stiffened plates are restrained at the edges. Because of the decreasing trend at low flame heating velocities, a minimum velocity of 19 in/min was chosen for the second pass.

Figure 4-2 shows the actual angular distortion removed versus inverse flame velocity for the second pass. The second pass shows about 50 % less scatter than the first pass and an increase in distortion removal as velocity decreases (see Figure 4-2). This was the relationship expected for the first heating pass also and further indicates that the first pass velocities were too slow.

Figures 4-3 through 4-6 show the actual angular

Fig 4—1: ANGULAR DISTORTION REMOVED

3/16" PLATE, 1ST PASS

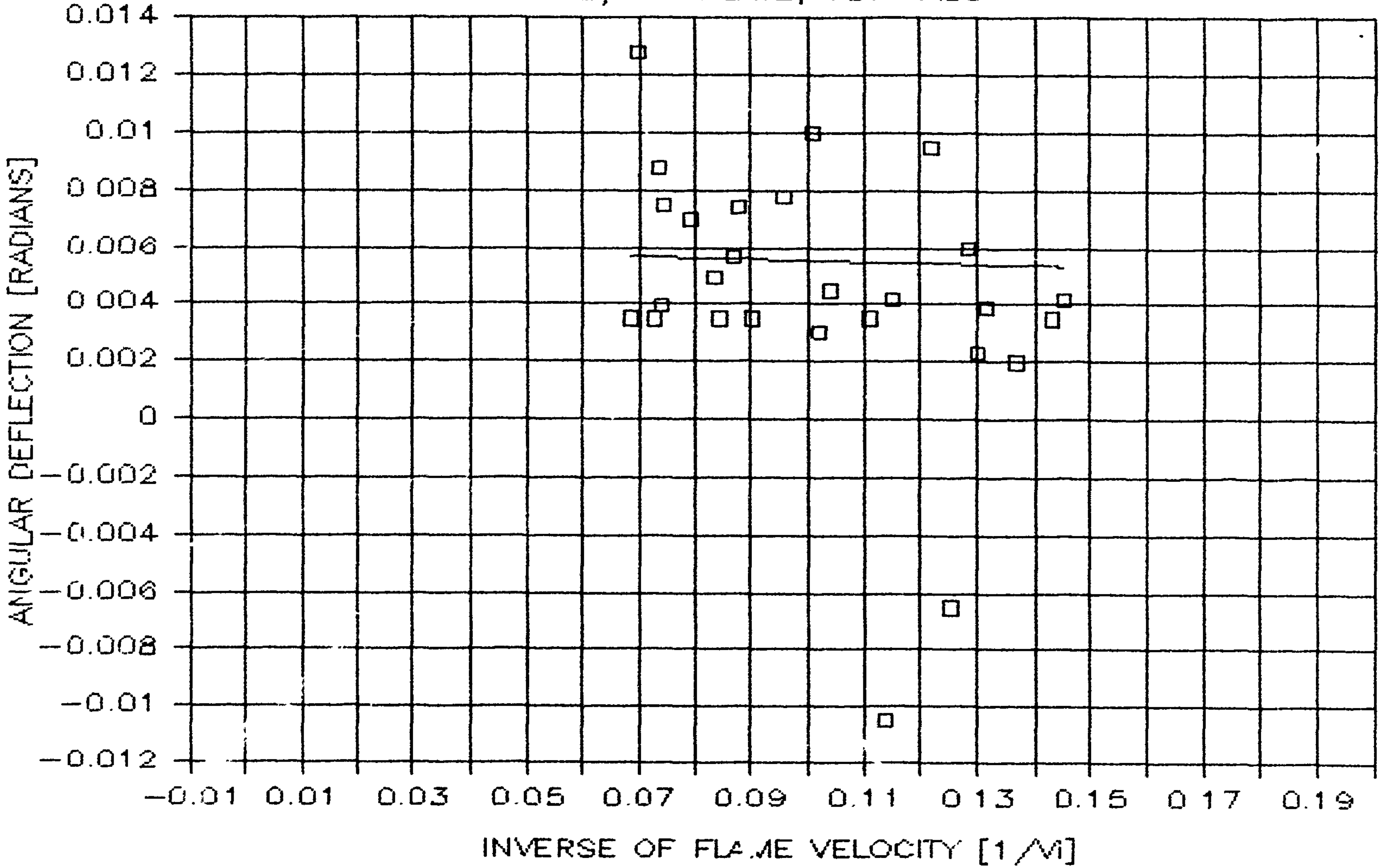
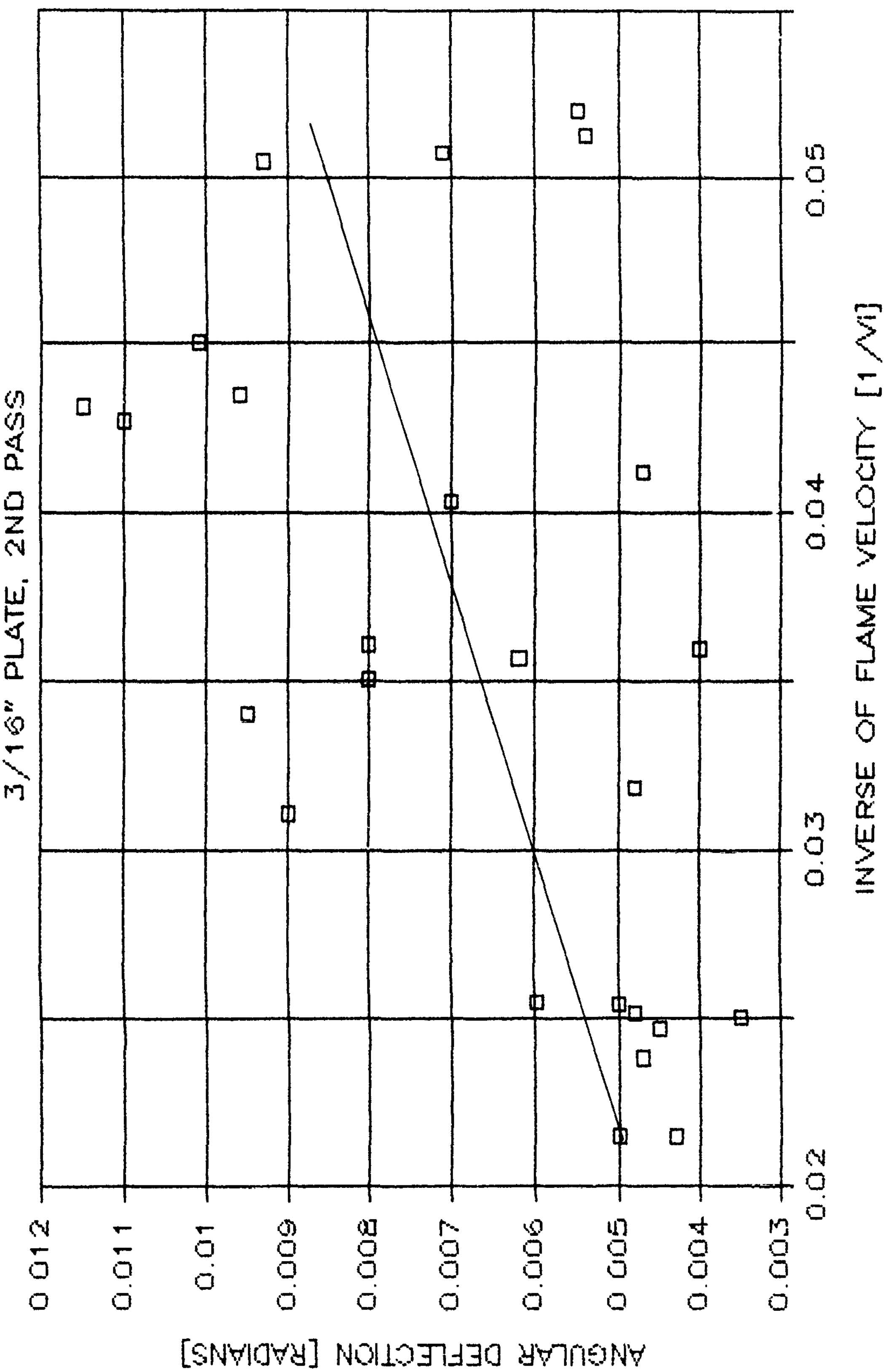


Fig 4-2: ANGULAR DISTORTION REMOVED

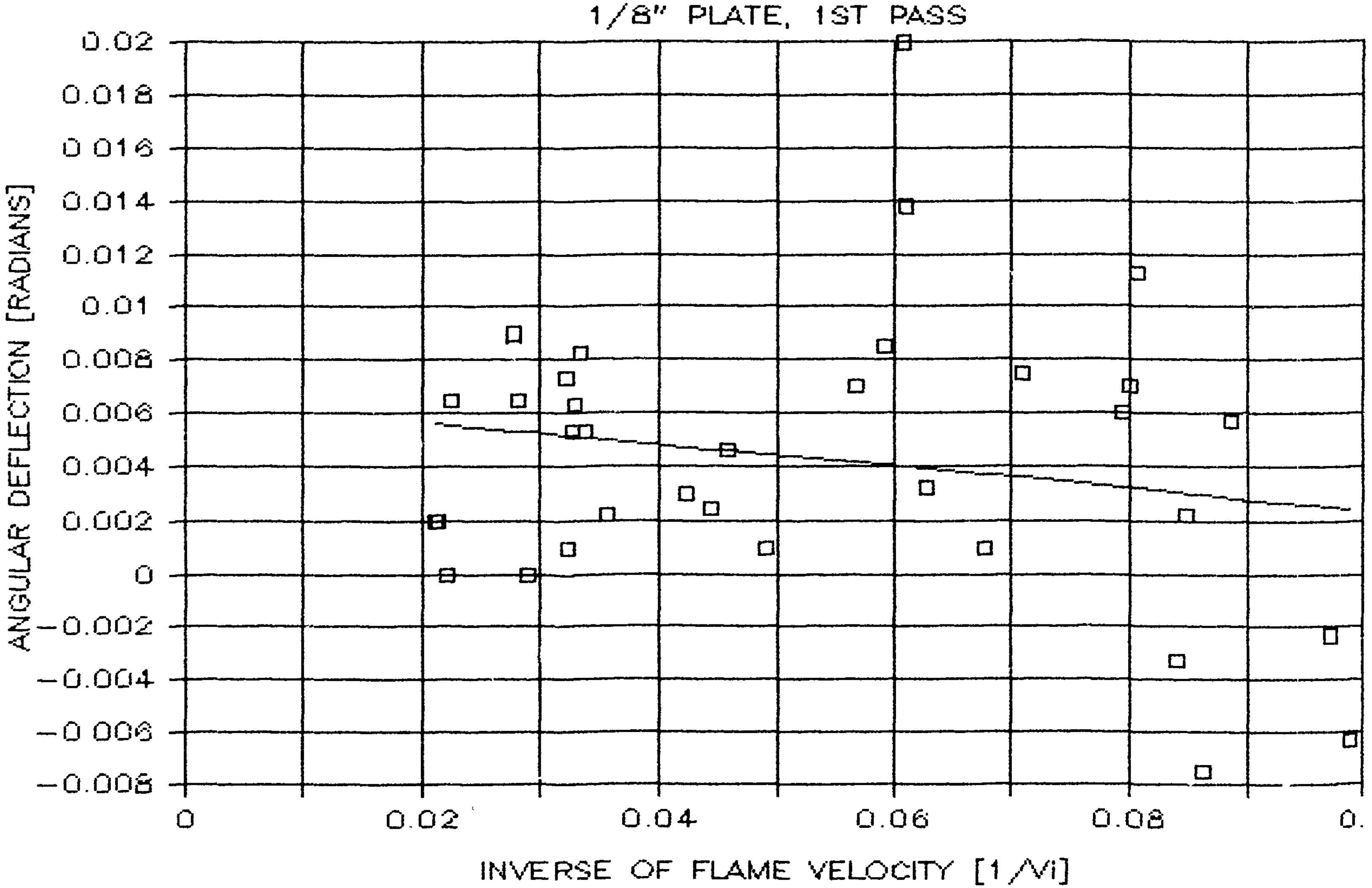


distortion removed versus inverse flame velocity for the four passes on the 1/8" stiffened plate. Figures 4-3 and 4-4 contain the results of the first and second passes. The trend is similar to that of the 3/16" plate. After the first pass, a minimum velocity of 19 in/min was chosen for the remaining flame heating passes.

The results of the first two line heating passes, of the 3/16" and 1/8" plates, indicate that the actual angular distortion removed versus inverse flame velocity (i.e. energy input) curve has the same general shape as the angular distortion removed versus heat input parameter [Q/(h*h)] curve for welding. See Figure 2-9. This indicates that, like welding, flame heating at low velocities may increase out-of-plane distortion.

Figures 4-5, and 4-6 are the graphs of the 3rd and 4th line heating passes, which were applied to panels #1 and #7 only. These two panels had an increase in angular distortion after the first line heating pass and were line heated further to determine the affect that continued line heating would have. Since the velocities used during these two passes were approximately 19.0 in/min, the important curve on each of these figures is that of average angular distortion removed. The average distortion removed during the 3rd and 4th line heating passes was 0.0085 rad and 0.0082 rad, respectively. The angular distortion removed during the 2nd pass at a velocity of 19.0 in/min (i.e. 1/v of 0.053) was about 0.0087. Although angular distortion removal was expected to decrease

Fig 4—3: ANGULAR DISTORTION REMOVED



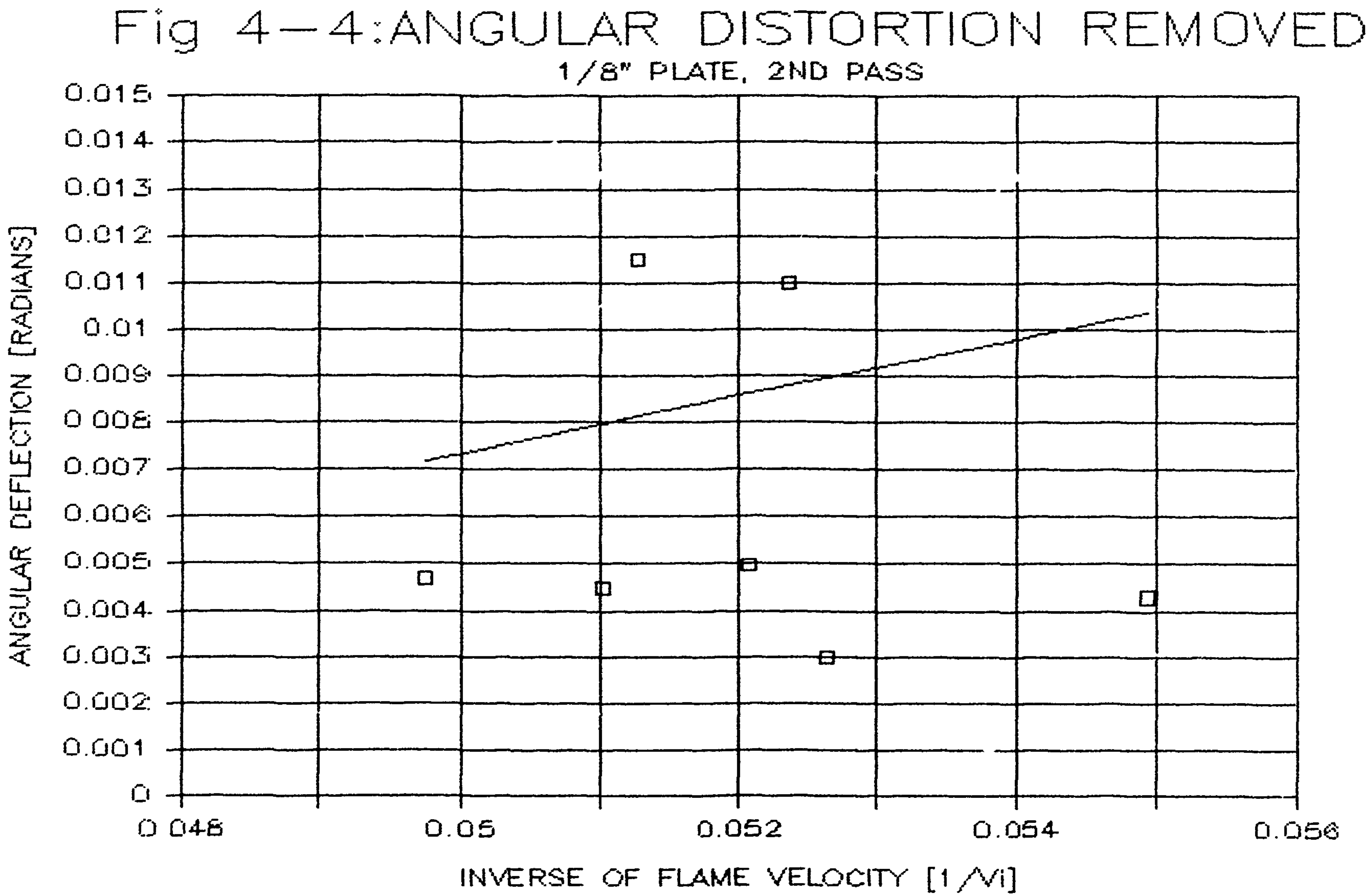


Fig 4-4:ANGULAR DISTORTION REMOVED
1/8" PLATE, 2ND PASS
ANGULAR DEFLECTION [RADIANS]
0.015
0.014
0.013
0.012
0.011
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0.048
0.05
0.052
0.054
0.056
INVERSE OF FLAME VELOCITY [1/Vi]

Fig 4-5: ANGULAR DISTORTION REMOVED

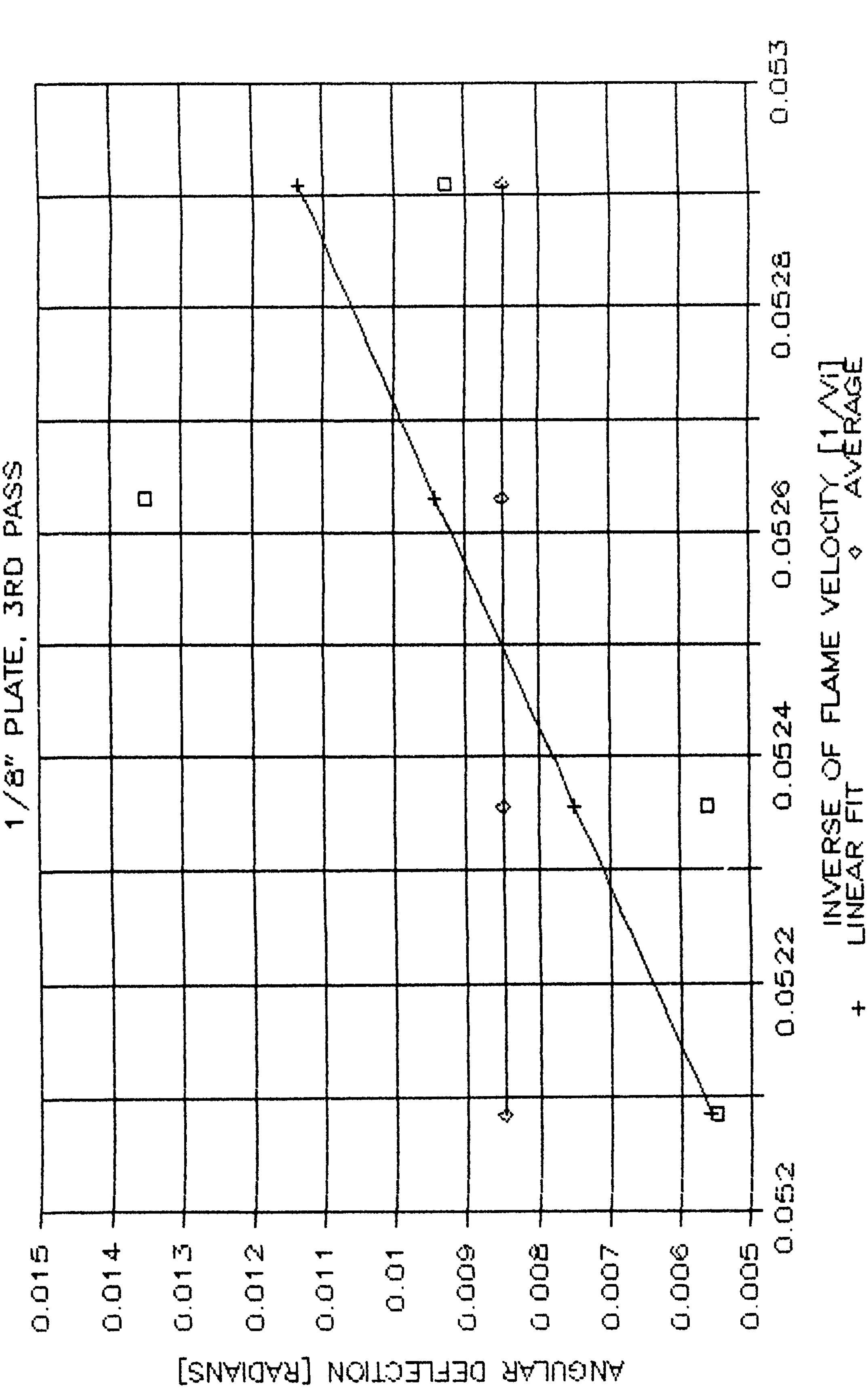
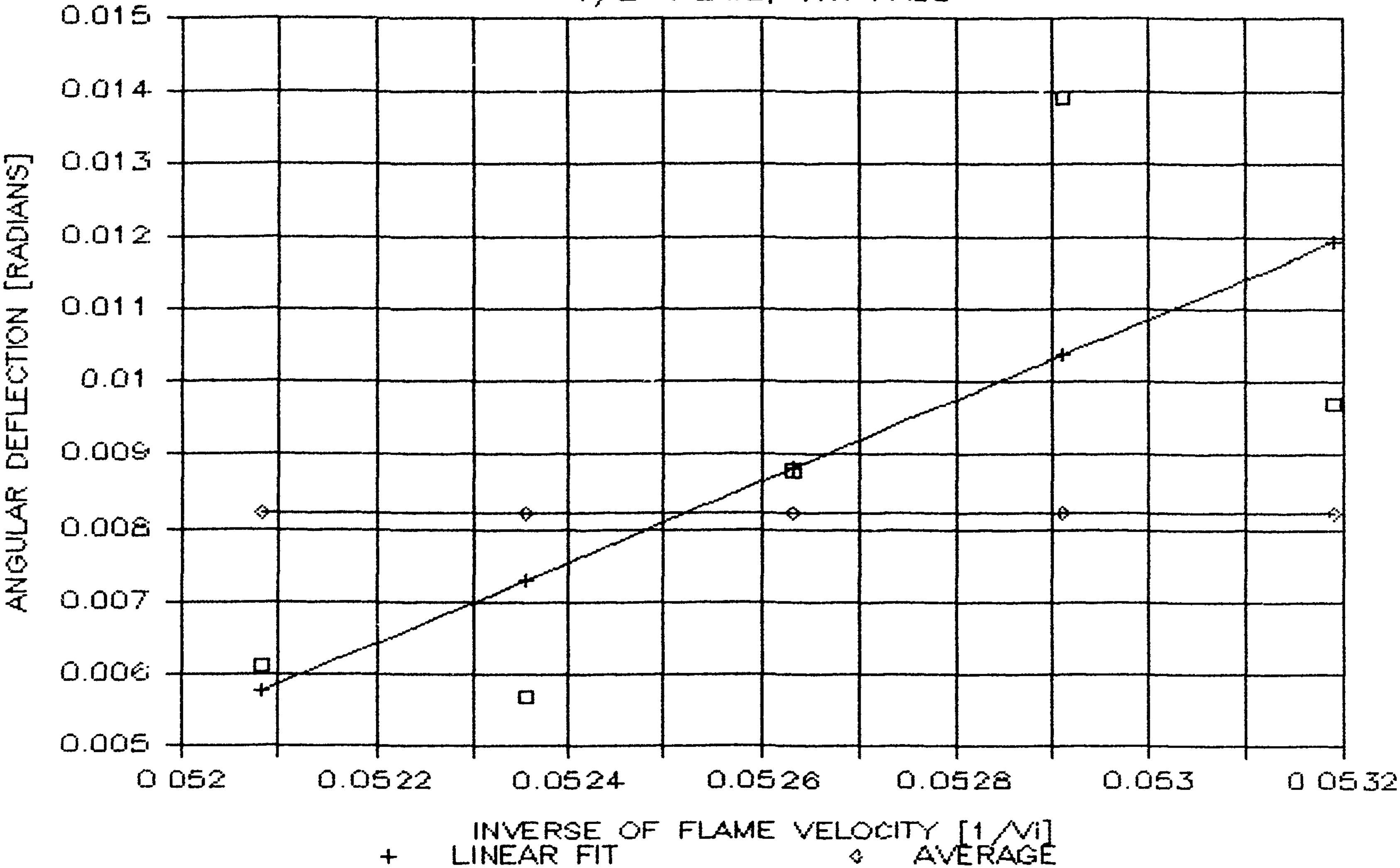


Fig 4-6: ANGULAR DISTORTION REMOVED

1/8" PLATE, 4TH PASS



during sequential line heating passes, these results show that the average distortion removed was virtually the same during passes 2, 3, and 4.

4.2 Line Heating Stiffened Plates

This section discusses the out-of-plane distortion caused by line heating the stiffened plate panels.

4.2.1 3/16" Plate

Figures 4-7 through 4-12 contain graphs of mid-panel deflections for the 3/16" stiffened plate recorded after welding, after all panels were flame heated the first time, and after all panels were flame heated the second time. These graphs were taken from Appendixes H and I. Figures 4-7, 4-8, and 4-9 contain the transverse mid-panel deflections and figures 4-10, 4-11, and 4-12 contain the longitudinal mid-panel deflections. Except for panel #4, these figures clearly show that line heating reduces angular distortion and that each heating pass removes more distortion. Refer to Tables 3.6 and 3.7. The average "Change in D(MAX)iT" and "Change in D(MAX)iL" during the first flame heating pass, not including panel #4, was 0.0244 and 0.0094 inches, respectively. The average "Change in D(MAX)iT" and "Change in D(MAX)iL" during the second pass was 0.0300 and 0.0291 inches, respectively. Thus, as discussed in section 4.1 for angular distortion removal, it appears that as the flame velocity decreases (i.e. 1/v increases) the out-of-plane distortion removed also increases, reaches a peak, and then decreases. The first

Fig 4—7: 3/16'' PLATE DEFLECTION

PANELS ONE, TWO, AND THREE

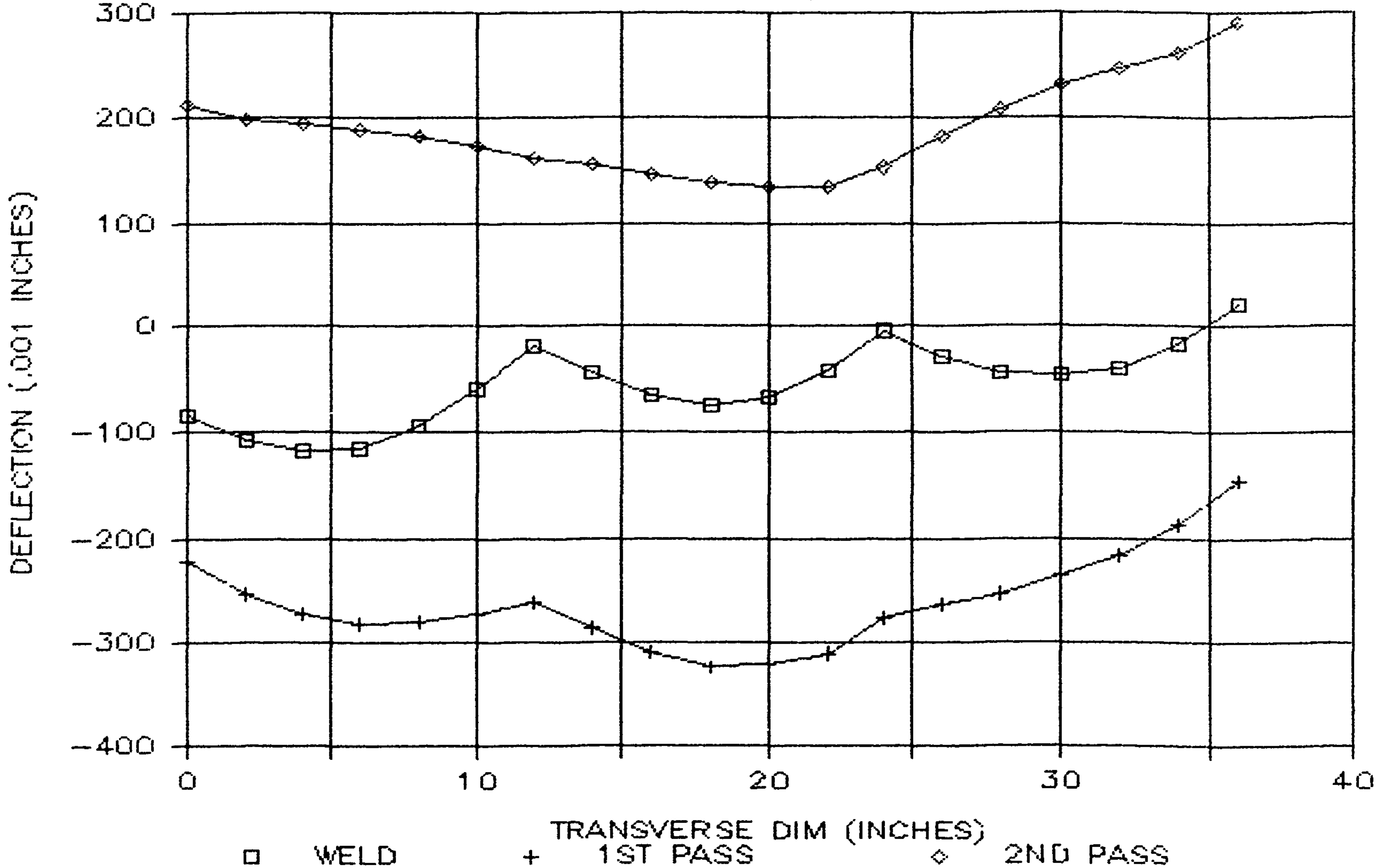
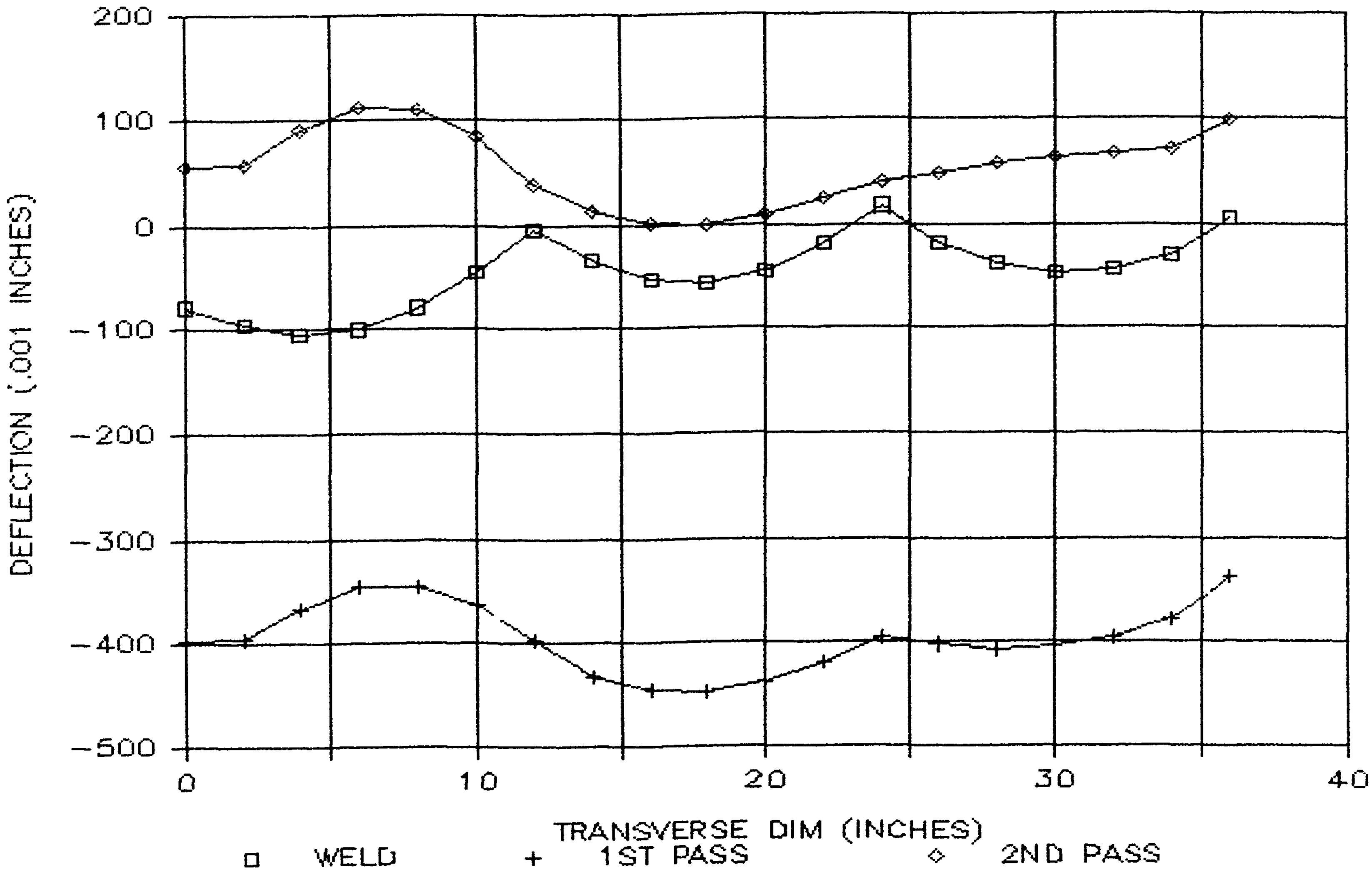


Fig 4–8: 3/16" PLATE DEFLECTION

PANELS FOUR, FIVE, AND SIX



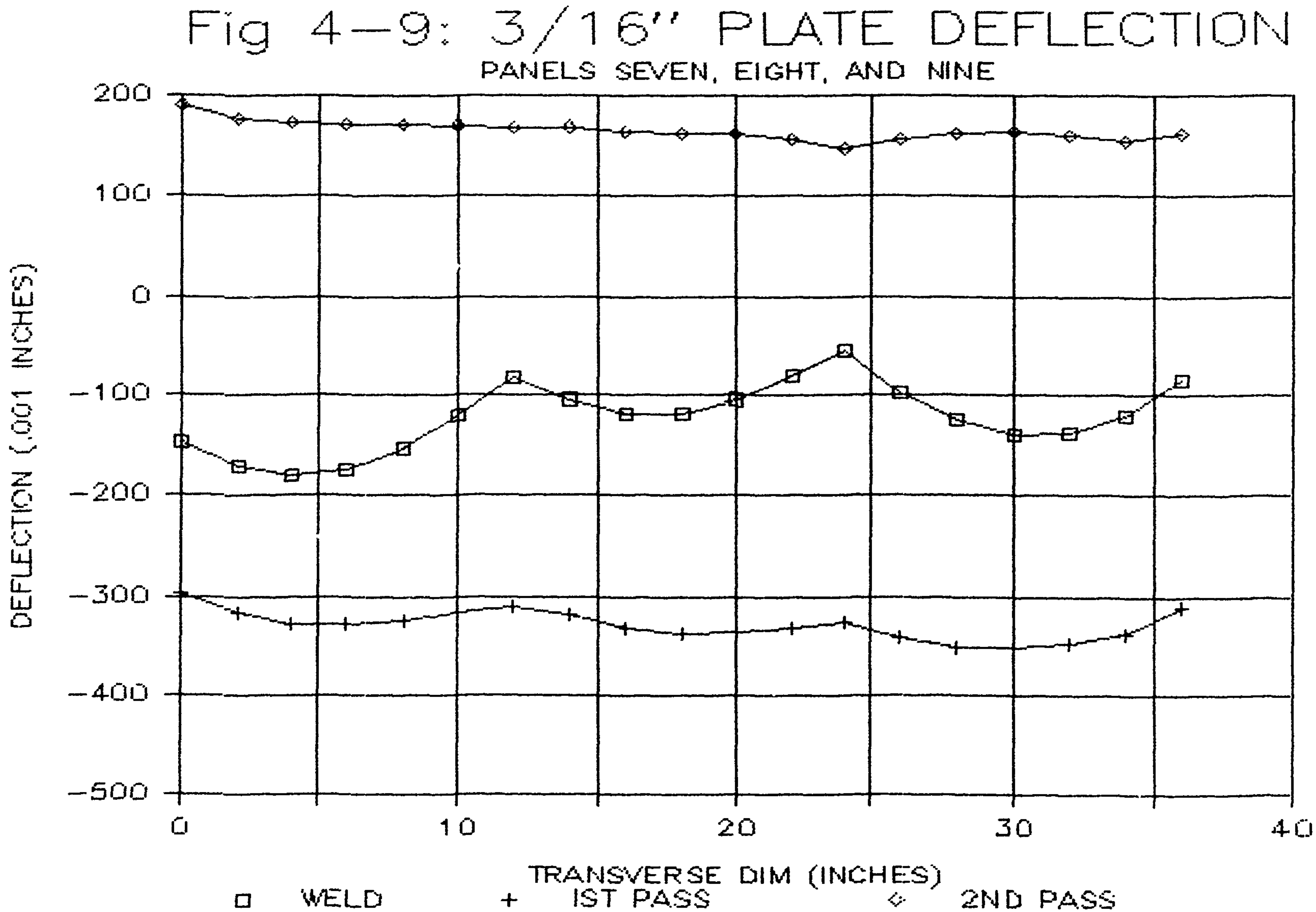
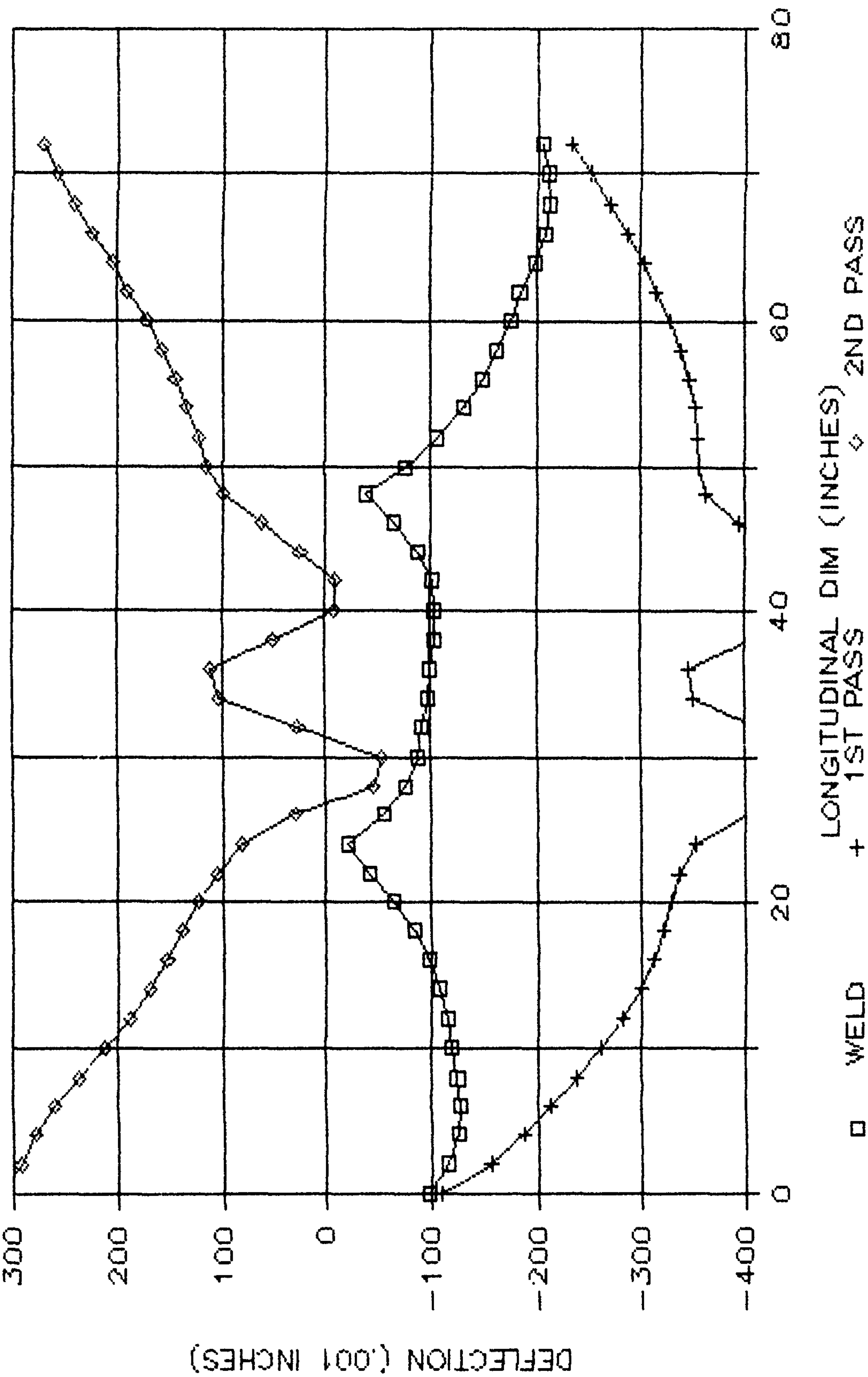


Fig 4—9: 3/16'' PLATE DEFLECTION
PANELS SEVEN, EIGHT, AND NINE
200
100
0
−100
−200
−300
−400
−500
DEFLECTION (.001 INCHES)
0
10
20
30
40
TRANSVERSE DIM (INCHES)
WELD
IST PASS
2ND PASS

Fig 4-10: 3/16'' PLATE DEFLECTION

PANELS ONE, FOUR, AND SEVEN



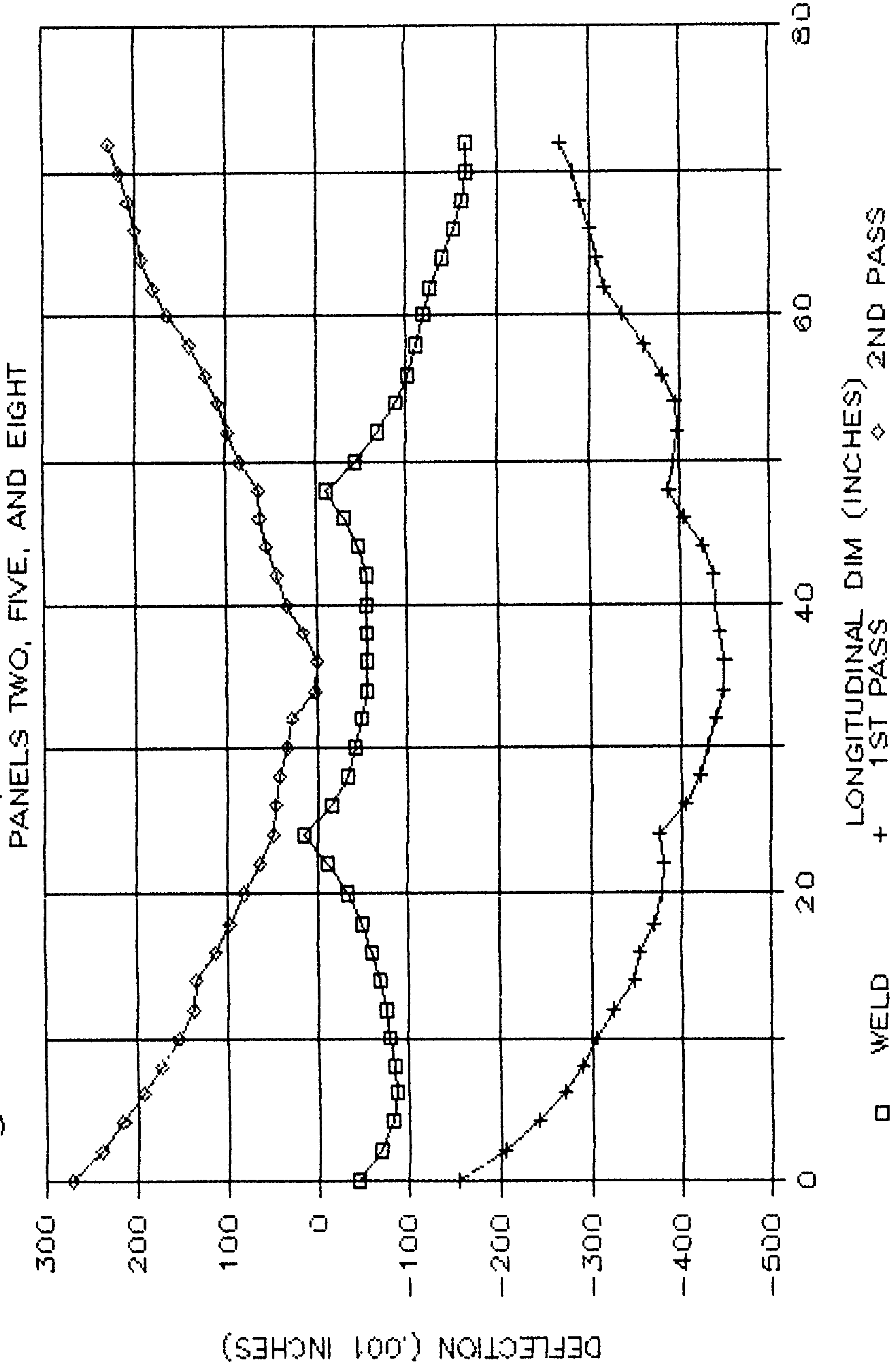
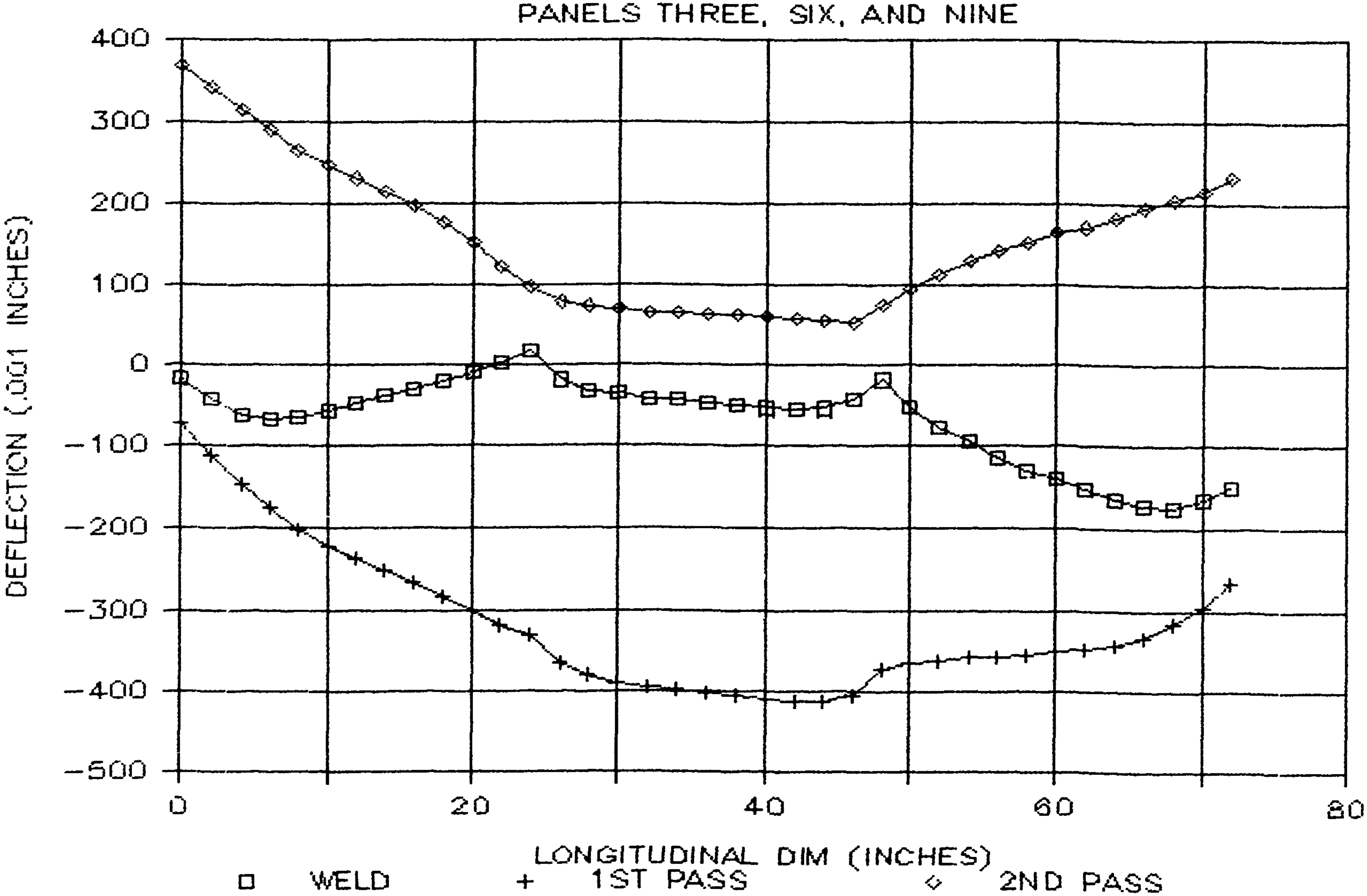


Fig 4—11: 3/16'' PLATE DEFLECTION

Fig 4-12: 3/16'' PLATE DEFLECTION



heating pass was performed at much lower velocities than the second pass. This could account for the smaller average distortion removed during the first pass as compared with that of the second pass.

Panel #4 shows buckling distortion. This was the only panel where line heating was applied to the outer edge first. It appears that this may have reduced the buckling strength of that panel. To minimize the probability of producing buckling distortion in the remainder of the panels the procedure described in section 2.4.3 was adopted.

4.2.2 1/8" Plate

Figures 4-13 through 4-18 contain graphs of mid-panel deflections for the 1/8" stiffened plate recorded after welding, after all panels were flame heated the first time, after all panels were flame heated the second time, and after panels #1 and #7 were flame heated the third and fourth times. These graphs were taken from appendixes J, K, and L. Figures 4-13, 4-14, and 4-15 contain the transverse mid-panel deflections and figures 4-16, 4-17, and 4-18 contain the longitudinal mid-panel deflections. With the exception of panels #1 and #7, these figures show that line heating reduces angular distortion and that each heating pass removes more distortion. Refer to Tables 3.8 and 3.9. The average "Change in D(MAX)iT" and "Change in D(MAX)iL" during the first flame heating pass, not including panels #1 and #7, was 0.0258 and 0.0217 inches, respectively. The average "Change in D(MAX)iT" and "Change in D(MAX)iL" during the second pass was 0.0396 and

Fig 4—13: 1/8'' PLATE DEFLECTION

PANELS ONE, TWO, AND THREE

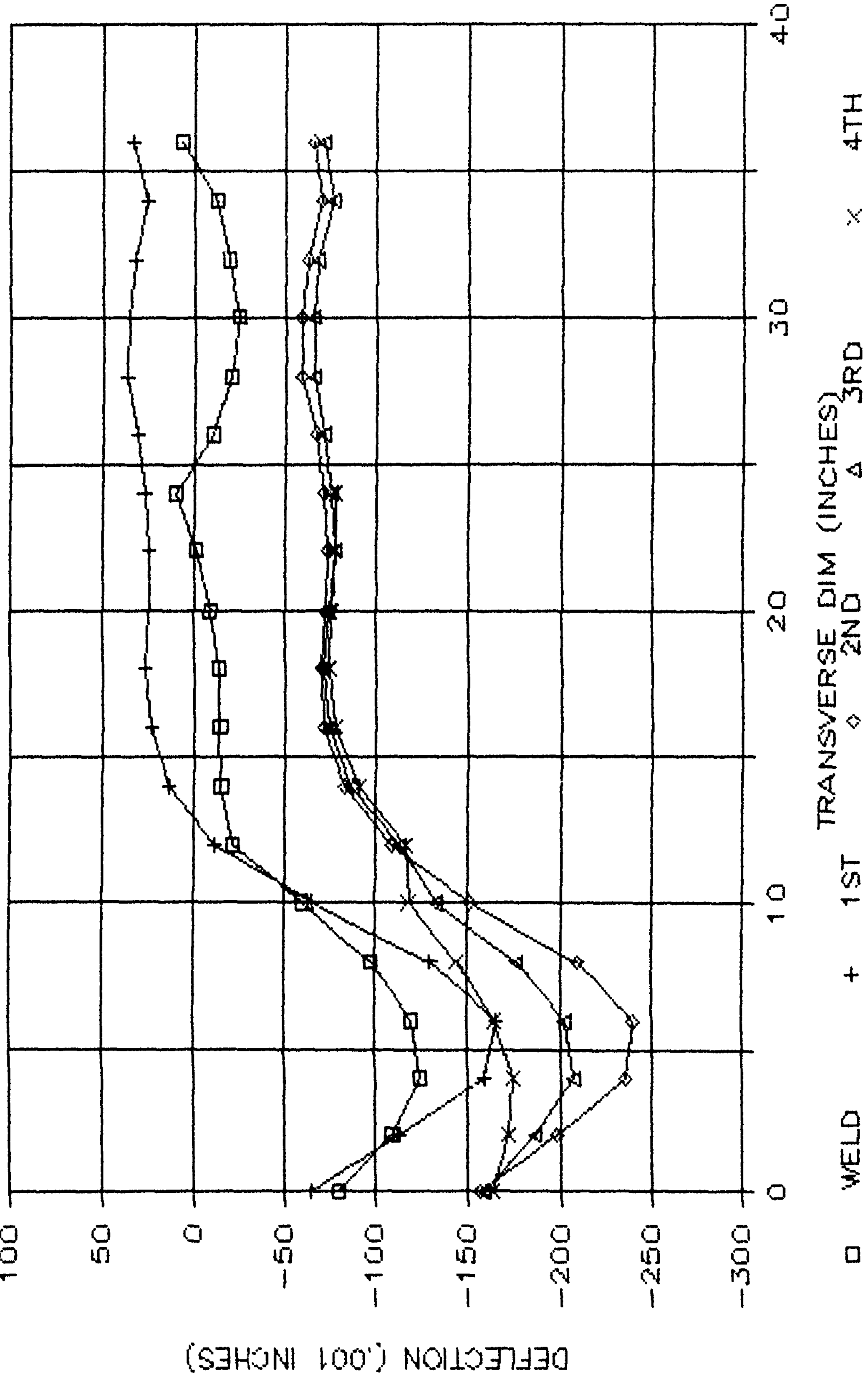


Fig 4—14: 1/8" PLATE DEFLECTION

PANELS FOUR, FIVE, AND SIX

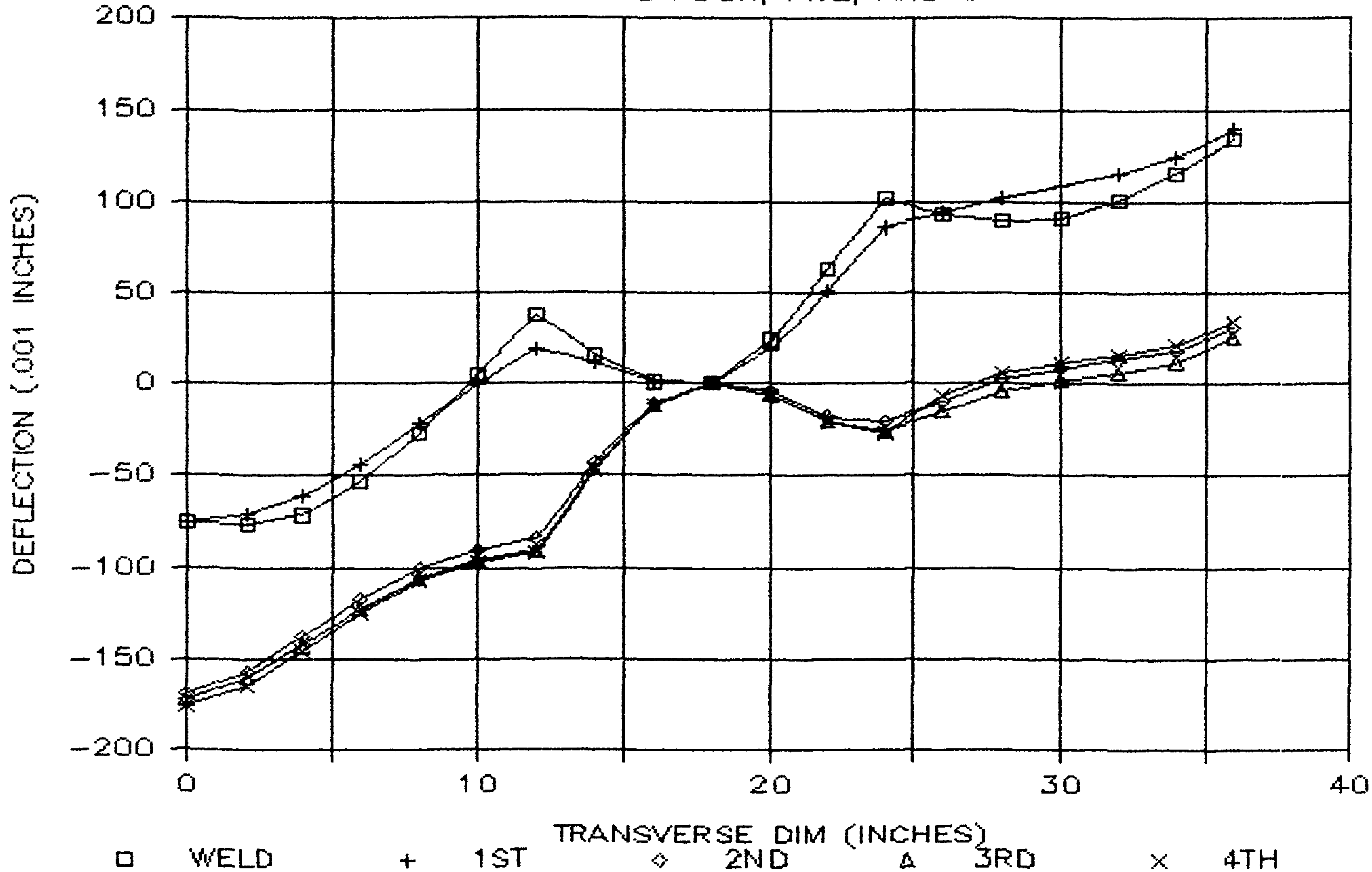


Fig 4—15: 1/8" PLATE DEFLECTION

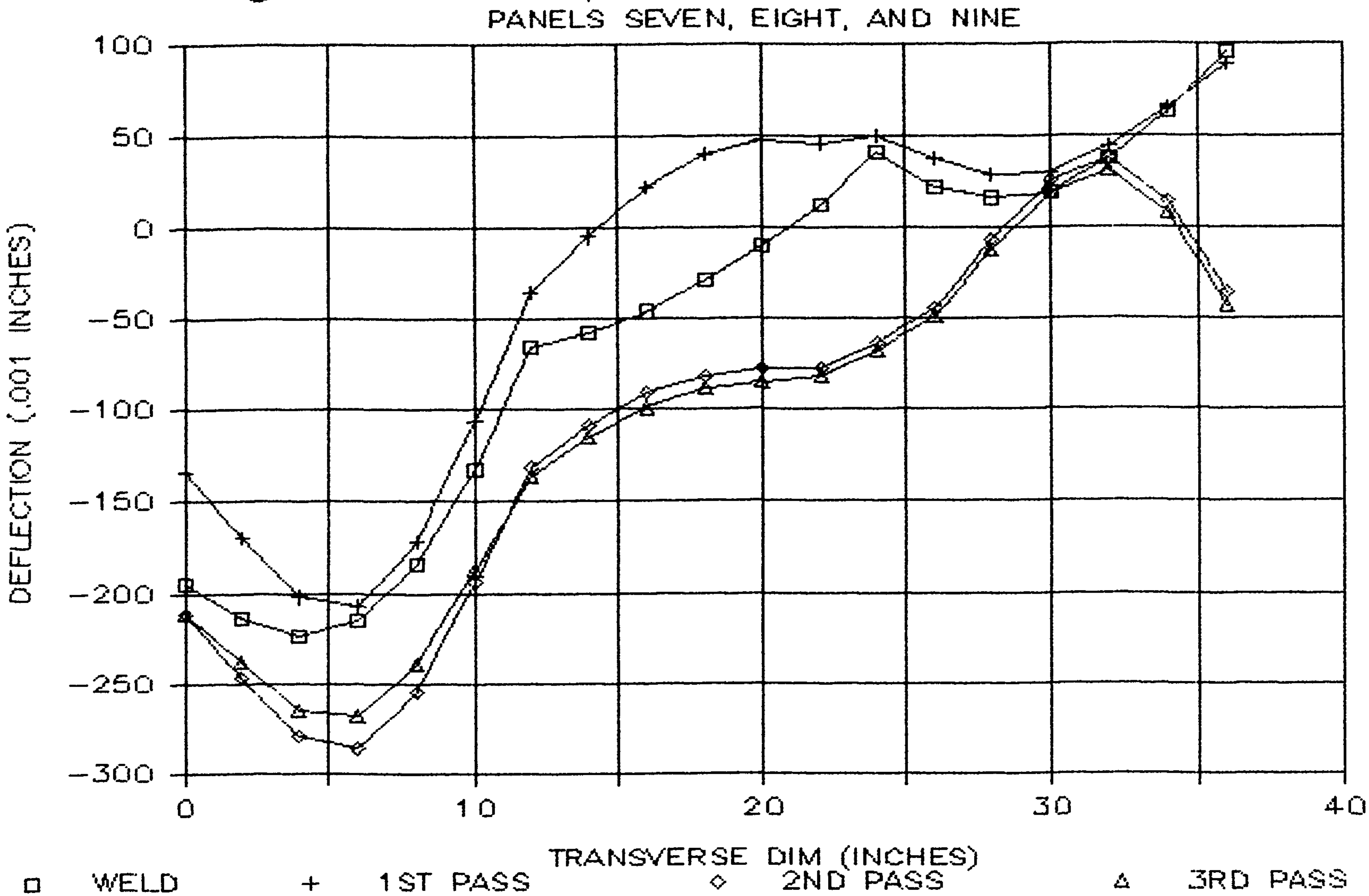


Fig 4—16: 1/8" PLATE DEFLECTION

PANELS ONE, FOUR, AND SEVEN

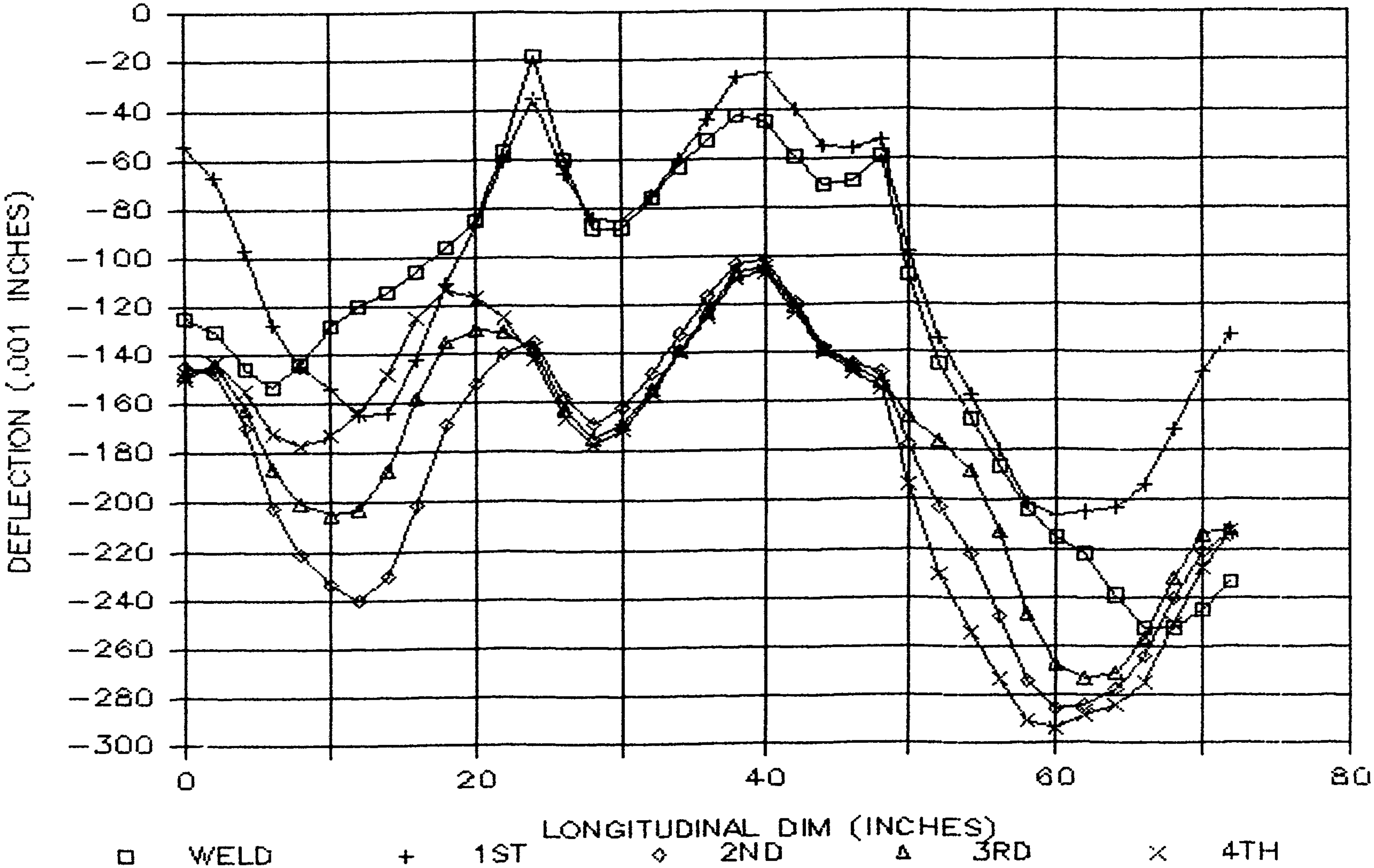
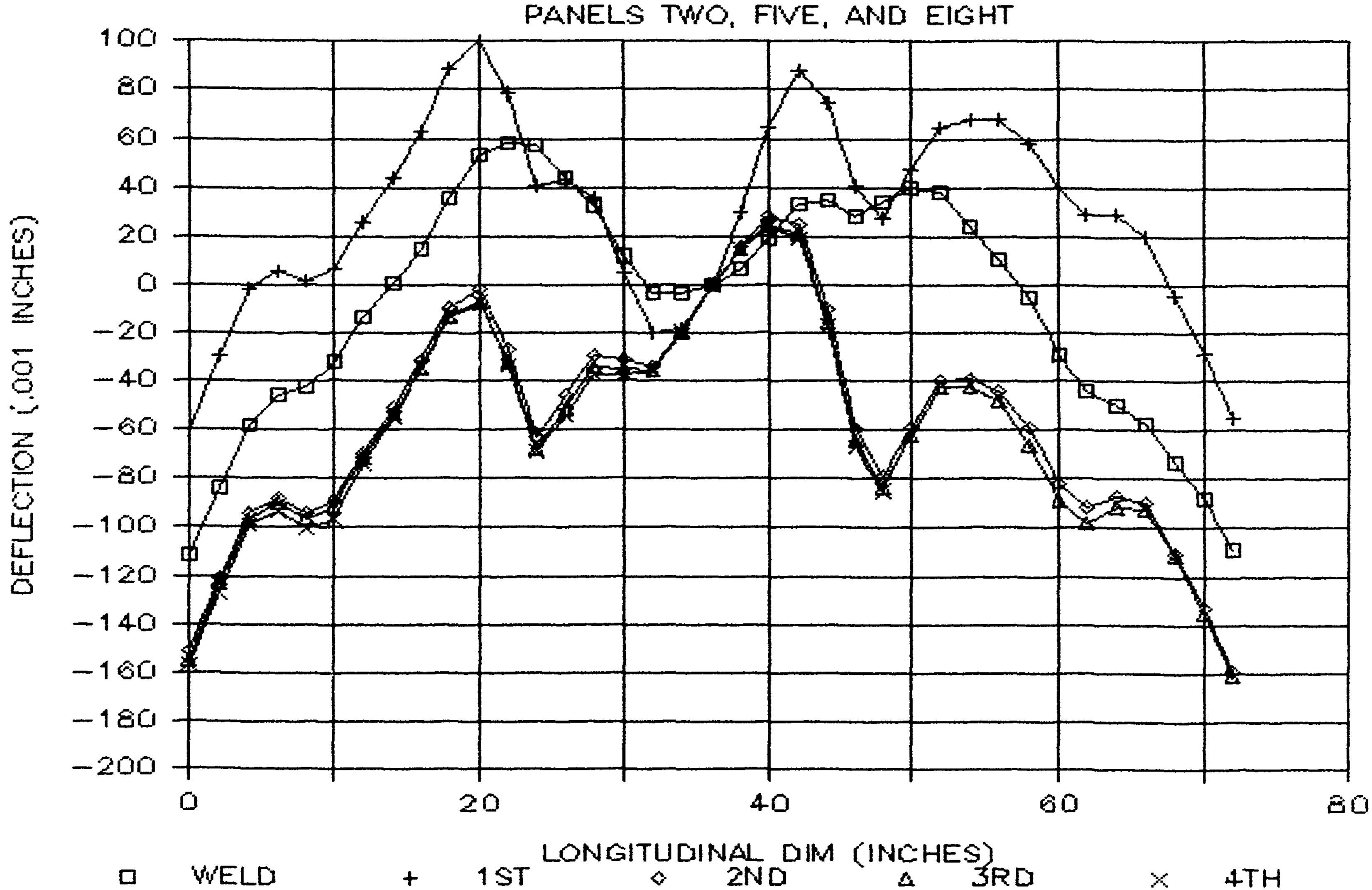


Fig 4—17: 1/8'' PLATE DEFLECTION



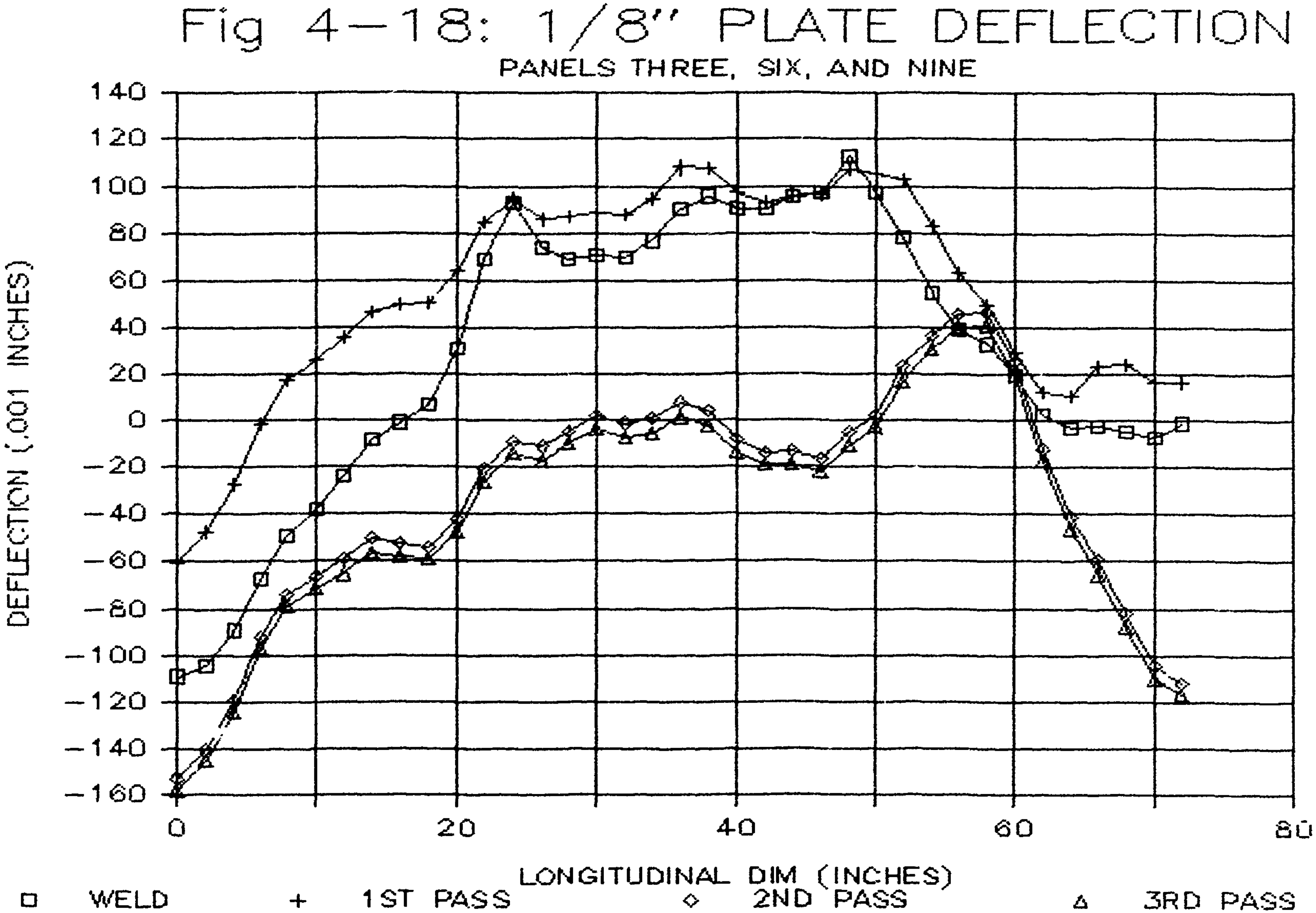


Fig 4—18: 1/8" PLATE DEFLECTION
PANELS THREE, SIX, AND NINE
DEFLECTION (.001 INCHES)
140
120
100
80
60
40
20
0
−20
−40
−60
−80
−100
−120
−140
−160
0
20
40
60
80
LONGITUDINAL DIM (INCHES)
WELD
1ST PASS
2ND PASS
3RD PASS

0.0393 inches, respectively. Again, it appears that the slow velocities of the first heating pass removed less distortion than when the velocities were increased during the second heating.

Panels #1 and #7 were flame heated at the lowest velocities (i.e. highest energy input) during the first heating pass. If line heating produces a functional relationship between out-of-plane distortion and velocity as shown in Figure 2-9 and discussed in section 4.1, then very low flame heating velocities could cause the increased distortion found in panels #1 and #7. When these panels were flame heated at velocities greater than 19.0 in/min (passes 2, 3, and 4) angular distortion decreased as expected.

Figures 4-16, 4-17, and 4-18 show that buckling is present in the longitudinal mid-panel and that applying linear flame heating has little effect on the buckling distortion but decreases the angular distortion.

4.3 Shape of Distortion Along the Panels

Appendixes M through U show the out-of plane distortion for the 3/16" stiffened plate after welding and after the first 5 line heating passes, as described in Chapter Three. The graphs show that the distortion patterns of these multi-panelled structures are similar to the distortion patterns shown by Duffy [11] and Shin [25] for single panel structures. The out-of-plane distortion increases as the distance from a stiffener (restraint) increases. Appendixes M through U also show that for the first flame heating pass:

1. as the panel was line heated the out-of-plane distortion decreased all along the panel, with more distortion removed as distance from stiffeners increased;
2. line heating a panel affects adjacent panels; and
3. buckling distortion was present in the 3/16" stiffened plate along the longitudinal direction, but to a lesser degree than in the 1/8" plate.

4.4 Mid-panel Deflections D(MAX)iT and D(MAX)iL

Appendixes V, W, X, and Y contain the mid-panel deflection data, D(MAX)iT and D(MAX)iL, for the 3/16" and 1/8" plates and tables comparing the affect that line heating one panel has on the other 9 panels. See each appendix description in section 3.2.

Both the 1/8" and the 3/16" plates were similarly affected by the first line heating passes. See appendixes X and Y. The panels were not isolated, since flame heating one panel affected the out-of-plane distortion of the adjacent panels as well as it's own. D(MAX)iT and D(MAX)iL in the panel that was line heated were decreased. D(MAX)iT and D(MAX)iL in the horizontal and vertical adjacent panels were decreased to a lesser amount than the heated panel or was minimally affected. D(MAX)iT and D(MAX)iL increased in the panel that was diagonally adjacent to the heated panel. It appears that line heating produced a moment about the stiffeners that separated the panels. When the out-of-plane distortion was reduced in the flame heated panel the moment

produced about the adjacent horizontal and vertical stiffeners was positive, which removed distortion in these panels also. As the distortion was decreased in these adjacent panels, a negative "secondary" moment was produced in their horizontal and vertical stiffeners. This secondary moment caused the panel that was diagonally adjacent to the heated panel to increase its out-of-plane distortion. For example, when panel #1 of the 3/16" plate was flame heated for the first time:

1. D(MAX)1T decreased by 0.00145 inches and D(MAX)1L decreased by 0.0018 inches;
2. D(MAX)2T and D(MAX)2L of panel #2 (the horizontal adjacent panel of panel #1) decreased by 0.013 inches and 0.008 inches, respectively;
3. D(MAX)4T and D(MAX)4L of panel #4 (the vertical adjacent panel of panel #1) decreased by 0.0038 inches and 0.0005 inches, respectively; and
4. D(MAX)5T and D(MAX)5L of panel #5 (the diagonal adjacent panel of panel #1) increased by 0.0083 inches and 0.0065 inches, respectively.

There were some exceptions to the above observations. When panels #2 and #8, of the 3/16" plate, were flame heated a negative moment was produced about the stiffener that connected them to panel #5, which caused D(MAX)5T and D(MAX)5L to increase. Also, when panel #5 was heated D(max) in both panels #2 and #8 increased. This could be caused by the added stresses on panel #5 as it was the only panel with no free edge and flame heating velocities were much slower (i.e. more

energy deposited) during the first pass. Panel #4 of the 3/16" plate buckled when heated, which caused the D(MAX) in all adjacent panels to decrease. D(MAX) in panel #6 of the 3/16" plate and panels #1 and #7 of the 1/8" plate increased when heated. This could have been do to the low flame heating velocities used. As described in section 4.1 when the flame velocity was low enough, it appears that the high energy input caused distortion to increase.

Both plates reacted similarly to the second flame heating passes. D(MAX) of all heated panels was reduced and in general all adjacent panels were not affected (i.e. the panels reacted to the second flame heating pass as though they were isolated from the rest of the plate). This could be do to the increased velocity (i.e. reduced energy input) during the second flame heating passes.

The third and fourth heating passes applied to panels #1 and #7 of the 1/8" plate exhibited a reduction in angular distortion and D(MAX) in the heated panels. There was no noticable change to the out-of-plane and angular distortion in the adjacent panels.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusion

The purposes of this research, given in section 1.8, have been accomplished. The conclusions of this investigation based on experimental results and the discussions in Chapter 4 are:

1. Line heating along the back side of fillet welds was an effective way of removing angular and out-of-plane distortion on 1/8" and 3/16" stiffened plates.
2. It appears that when the flame heating velocity decreased and more energy was deposited into the plate, the amount of distortion removed increased, reached a plateau, and then decreased; the plateau occured around 19 to 24 in/min. in both stiffened plates.
3. The affect of line heating was not limited to the heated panel. Adjacent panels were also affected. This was most apparent at low flame heating velocities (i.e. velocities less than 14 in/min. or 1/v greater than 0.070 min/in).
4. Line heating applied along the stiffeners in a panel structure did not affect buckling distortion, but did reduce angular distortion along the edges of the buckled panel.
5. The actual angular distortion removed for a given velocity, in the stiffened plate structure, was a small

fraction of that predicted by the free-end sample relationship (Figures 2-17 and 2-18). However, the magnitude of the free-end sample relationship was within a power of 10 of the actual stiffened plate relationship.

5.2 RECOMMENDATIONS FOR FUTURE RESEARCH

This first study provided a good estimate for the out-of-plane and angular distortion removed versus flame heating velocity. Further investigation is required to increase the data base and improve the reliability of the distortion removed versus inverse velocity functional relationship.

Further research in removal of distortion in stiffened plates using flame heating should be investigated. These studies should investigate the reduction of all forms of distortion by using a combination of line heating along the back side of stiffeners, spot heating, line heating away from stiffeners, and contour-line heating (discussed by T. Borzecki and K.Rosochowicz [6]).

APPENDIX A

NOMENCLATURE

CHANGE in D(MAX)iT	The change in out-of-plane distortion at the middle transverse line of panel #i, in inches.
CHANGE in D(MAX)iL	The change in out-of-plane distortion at the middle longitudinal line of panel #i, in inches.
d	Angular distortion, in radians.
d(ai)	Angular distortion in the free-end sample after the i-th heating pass, in radians.
d(abi)	Angular deflection at the middle line on the panel # i side of the stiffener between points a & b, in radians.
d(abci)	Angular deflection on panel #i side of the stiffener, between stiffener points a & b, in radians. The c designates either L or t.
d(abLi)	Longitudinal angular deflection on panel # i side of the stiffener between stiffener points a & b, in radians.
d(abti)	Transverse angular deflection on panel #i side of side of the stiffener between stiffener points a & b, in radians.
Df	Average weld size, in inches.
d(ri)	Angular distortion removed in the free-end sample during line heating pass # i, in radians.
d(ri)act	Actual angular distortion removed from a stiffened plate panel due to line heating that panel, in radians.
d(r1)	d(w) -d(a1), angular distortion removed in the free-end sample during the first heating pass, in radians.
d(r2)	d(a1) - d(a2), angular distortion removed in the free-end sample during the 2nd heating pass, in radians.
d(rci)	Reference angle in the stiffened plate for panel #i, in radians. The c stands for either L or t.
d(rLi)	Panel # i longitudinal reference angle, in radians.

d(rti)	Panel # i transverse reference angle, in radians.
d(w)	Angular distortion in the free-end sample after welding, in radians.
D(i,j)	Out-of-plane distortion measurements in the stiffened plate, in inches.
D(t,L)	Same as D(i,j).
D(MAX)	Out-of-plane distortion at center of panel, in inches.
D(MAX)iT	D(MAX) on the middle transverse line of panel # i, in inches.
D(MAX)iL	D(MAX) on the middle longitudinal line of panel # i, in inches.
h	plate thickness, in inches.
H	Out-of-plane distortion measurements of the free-end sample, in inches.
H(ai)	Average out-of-plane distortion of the free-end sample after line heating pass # i, in inches.
H(aw)	Average out-of-plane distortion of the free-end sample after welding, in inches.
I	Welding current, in amps.
L	Free-end sample plate transverse dimension, in inches.
Q	Net heat or effective thermal power of welding arc, in cal/cm.
Q/(h*h)	Heat input parameter, in cal/(cm**3).
v	Flame heating velocity, in in/min.
v(abi)	Line heating velocity applied to the panel # i side of the stiffener between points a & b, in in/min.
v(act)	Actual flame heating velocity applied to the stiffened plate, in/min.
v(i)	Flame heating velocity during pass # i, in in/min.
V	Welding voltage, in volts.

APPENDIX B

FUNDAMENTALS OF LINE HEATING

The line heating fundamentals described in this appendix were based on applying heat to ordinary mild steel plates using an oxy-acetylene torch [5]. These fundamentals apply to flame straightening as well as to flame bending.

The parameters that govern the degree of deformation which occurs during line heating are:

-torch-tip type and size

-distance between torch-tip and metal plate,

-torch travel speed,

-cooling method (water or air),

-gas, oxygen, and water flow rates,

-distance between heating center and cooling center,

-plate thickness,

-material type, and

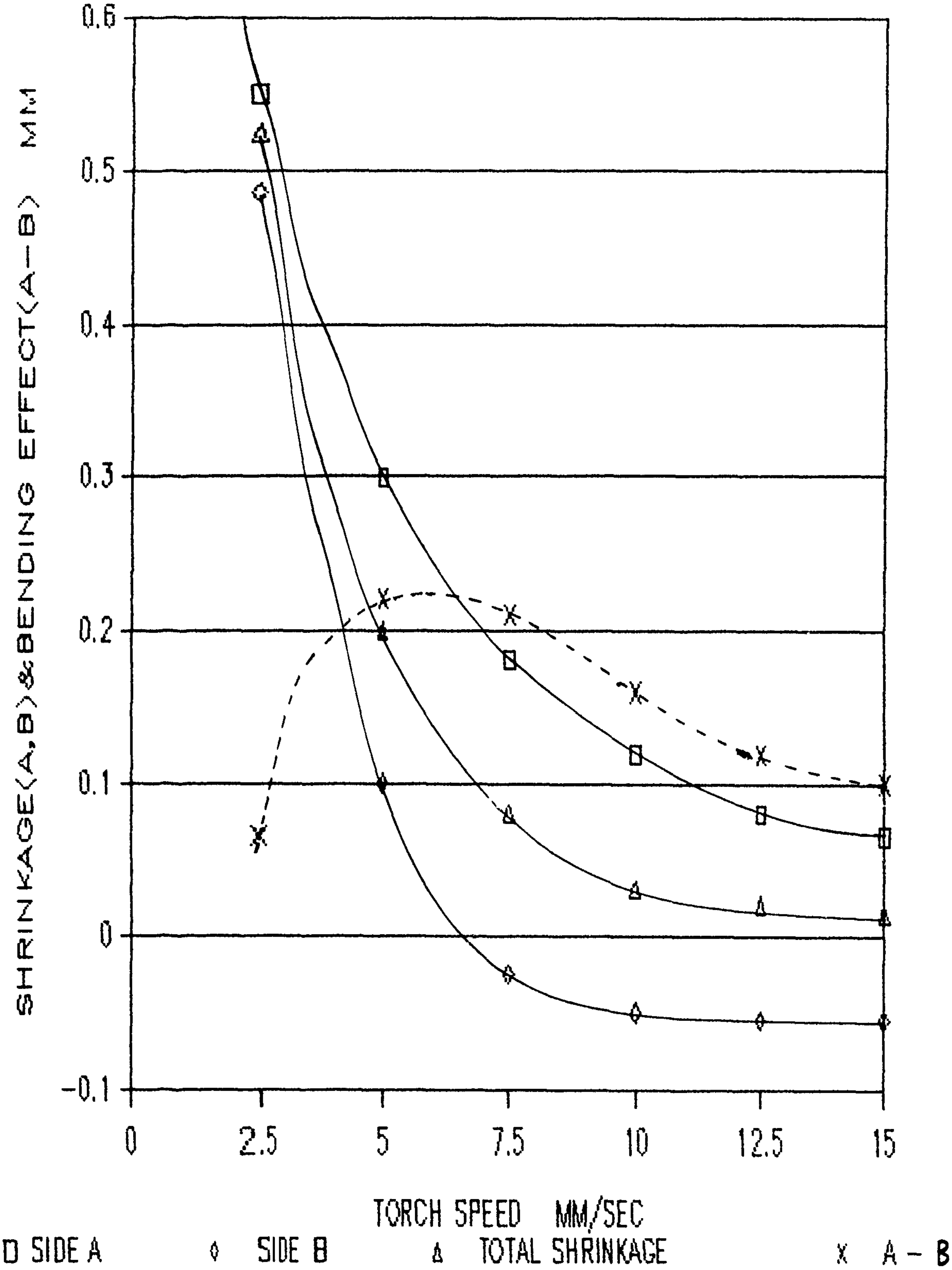
-stresses mechanically applied before line heating.

With torch speed as the only variable, the unbalanced shrinkage between top and bottom surfaces causes bending, see Figure B-1. The bending effect is defined as the difference between the shrinkage on the heated side (A) and the shrinkage on the unheated side (B) of a plate. Figure B-1 shows that:

1. at very low speeds (high temperatures), total shrinkage is large and the bending effect is small,
2. as speed increases, shrinkage decreases exponentially while the bending effect increases relatively fast,

Fig B-1: SHRINKAGE & BENDING EFFECT

BENDING CAUSED BY UNBALANCED SHRINKAGE



passes through a maximum value, and thereafter reduces gradually, and

3. there is only a limited useful range of speeds at which both acceptable shrinkage and near maximum bending effect are obtainable (around the peak in the A - B curve).

Figures B-2, B-3, and B-4 were obtained by varying plate thickness, travel speed, and initial stress while all other parameters were held constant [5]. It is clear from these figures that:

-the angular distortion (bending) shown in Figure B-2, particularly for t=14mm, are clearly related to bending effect as plotted in Figure B-1, and

-the existence of initial stress as shown in Figure B-3 and particularly the increased stress shown in Figure B-4, result in increased amounts of permanent deformation after line heating.

Obviously, applied initial stresses greatly facilitate bending by line heating.

Figure B-5 shows the effect of applying subsequent heat passes on the same line, the bending effect diminished with each successive pass [5,26]. Figure B-6 shows that when subsequent line heating passes were greater than 30 mm apart, there was no reduction in the bending effect [4].

Fig B-2: DISTORTION VS SPEED

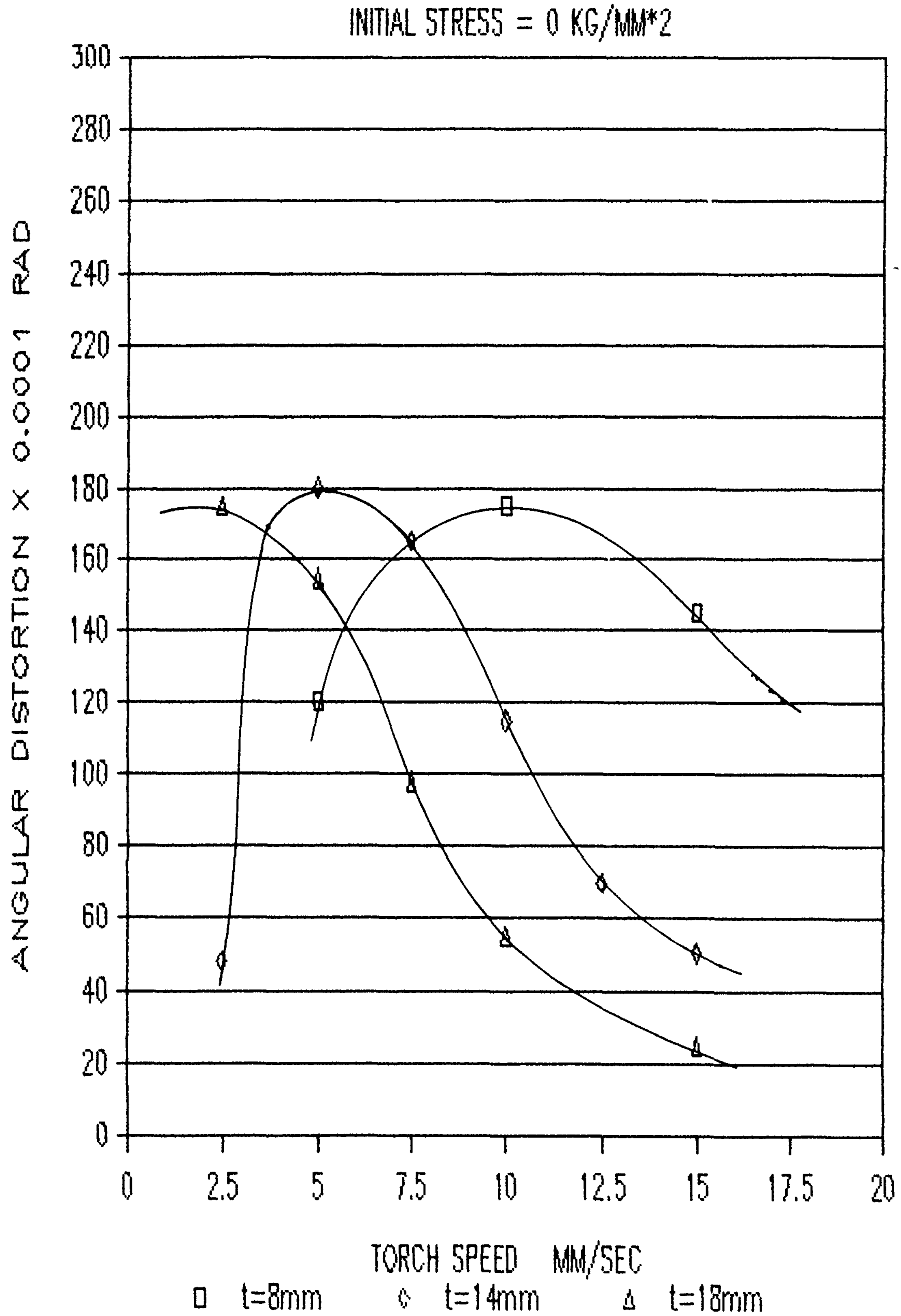


Fig B-3: DISTORTION VS SPEED

INITIAL STRESS = -8 KG/MM*2

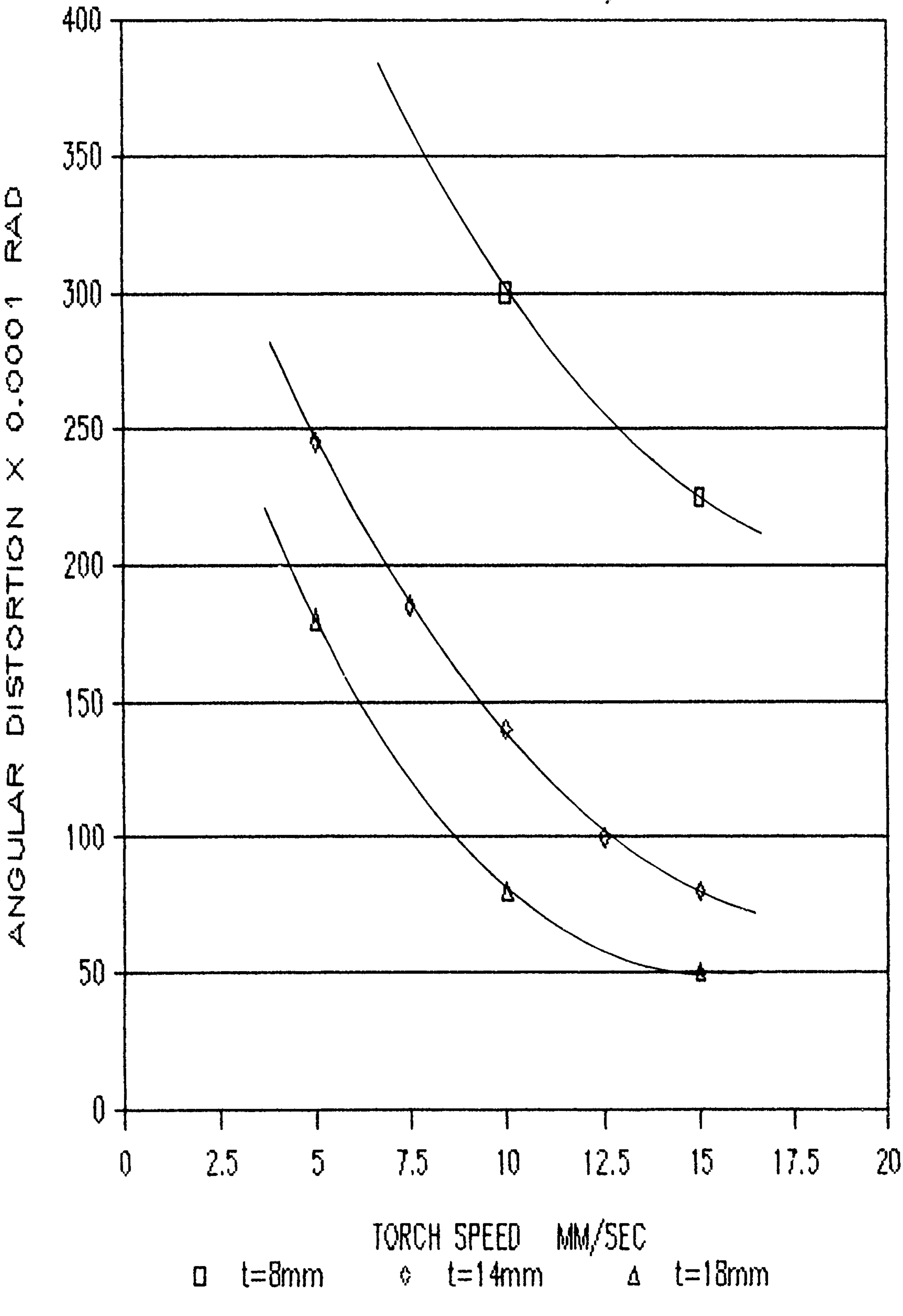


Fig B-4: DISTORTION VS SPEED

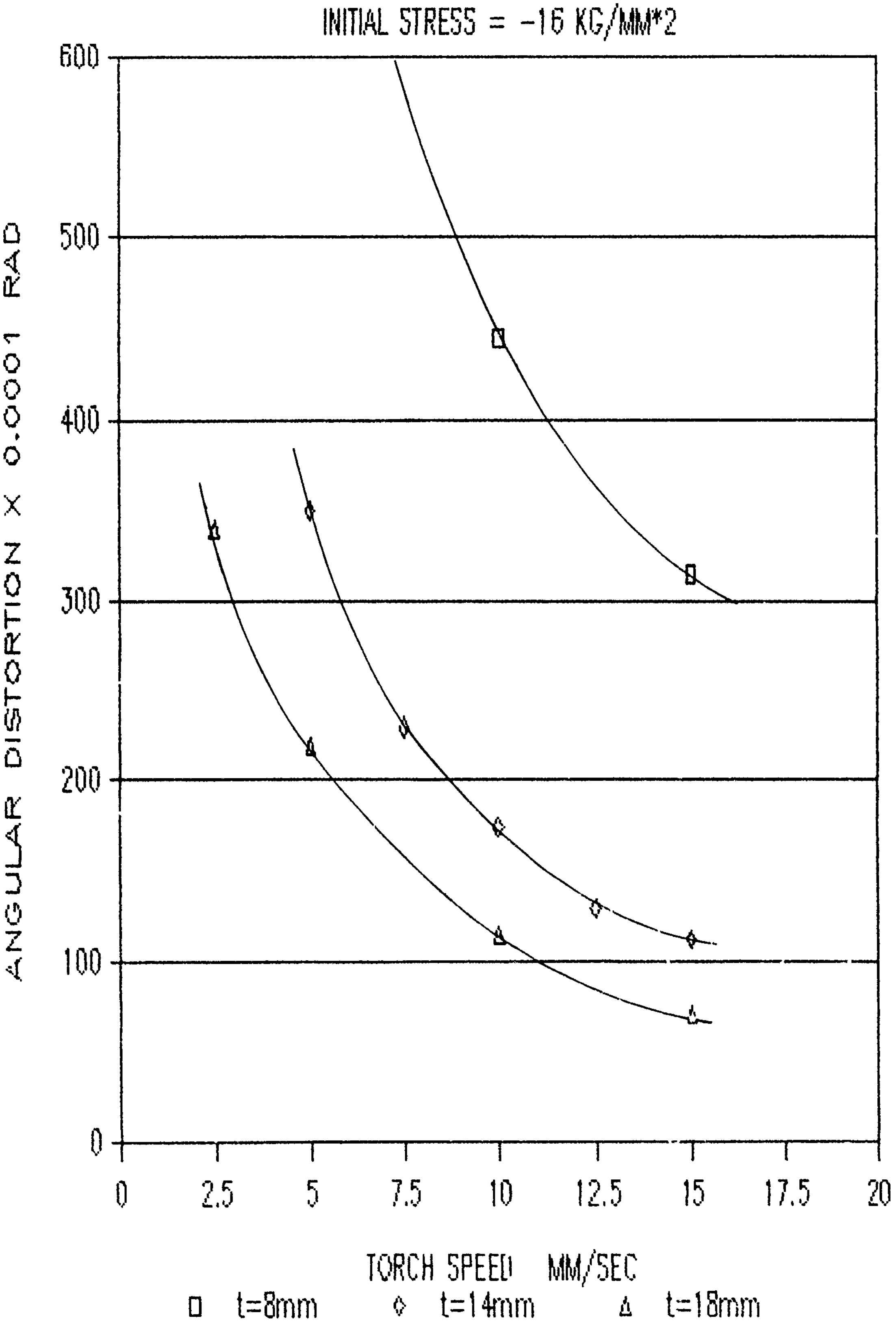
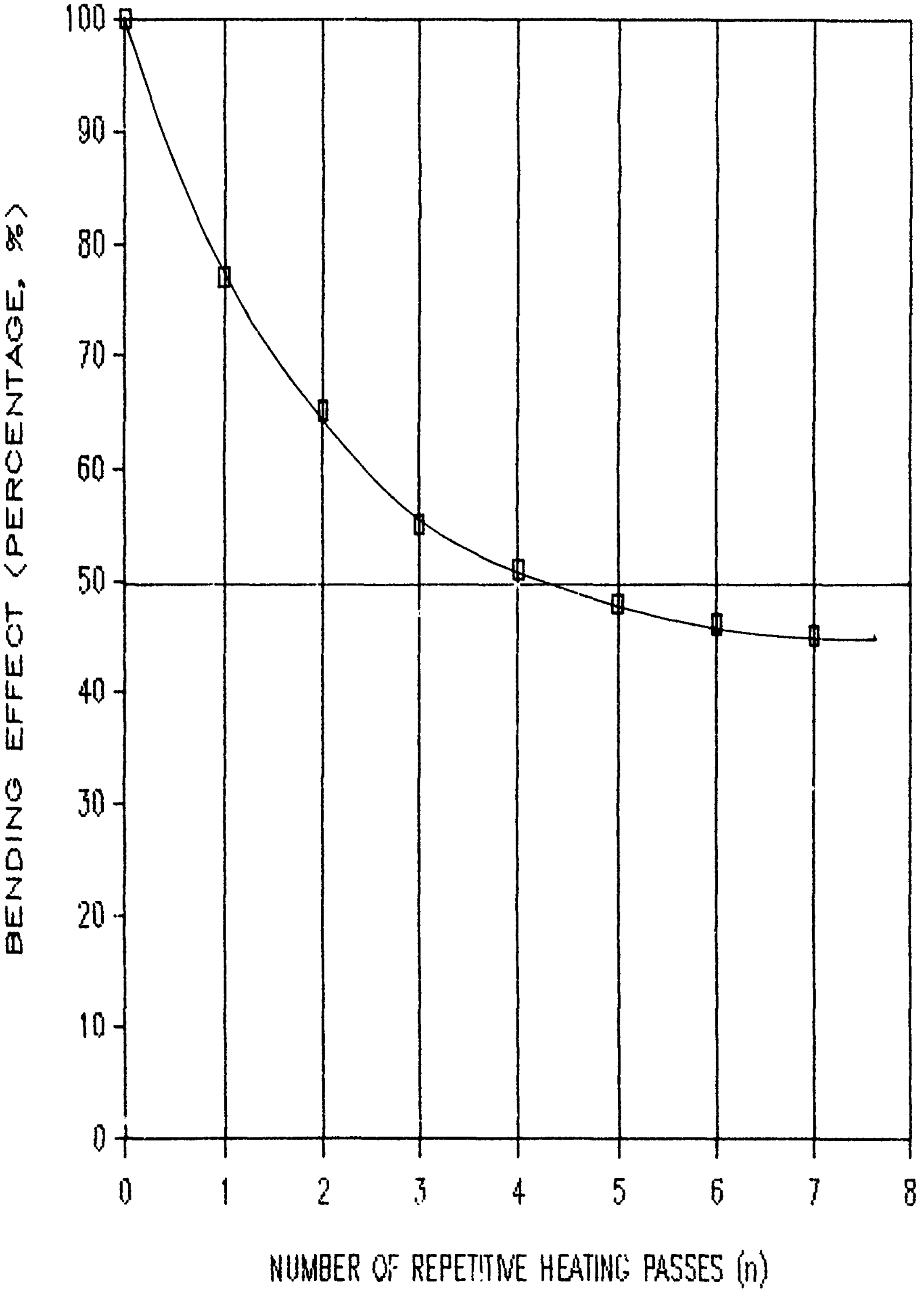


Fig B-5: BENDING EFFECT

FROM REPETITIVE HEATING, SAME PATH



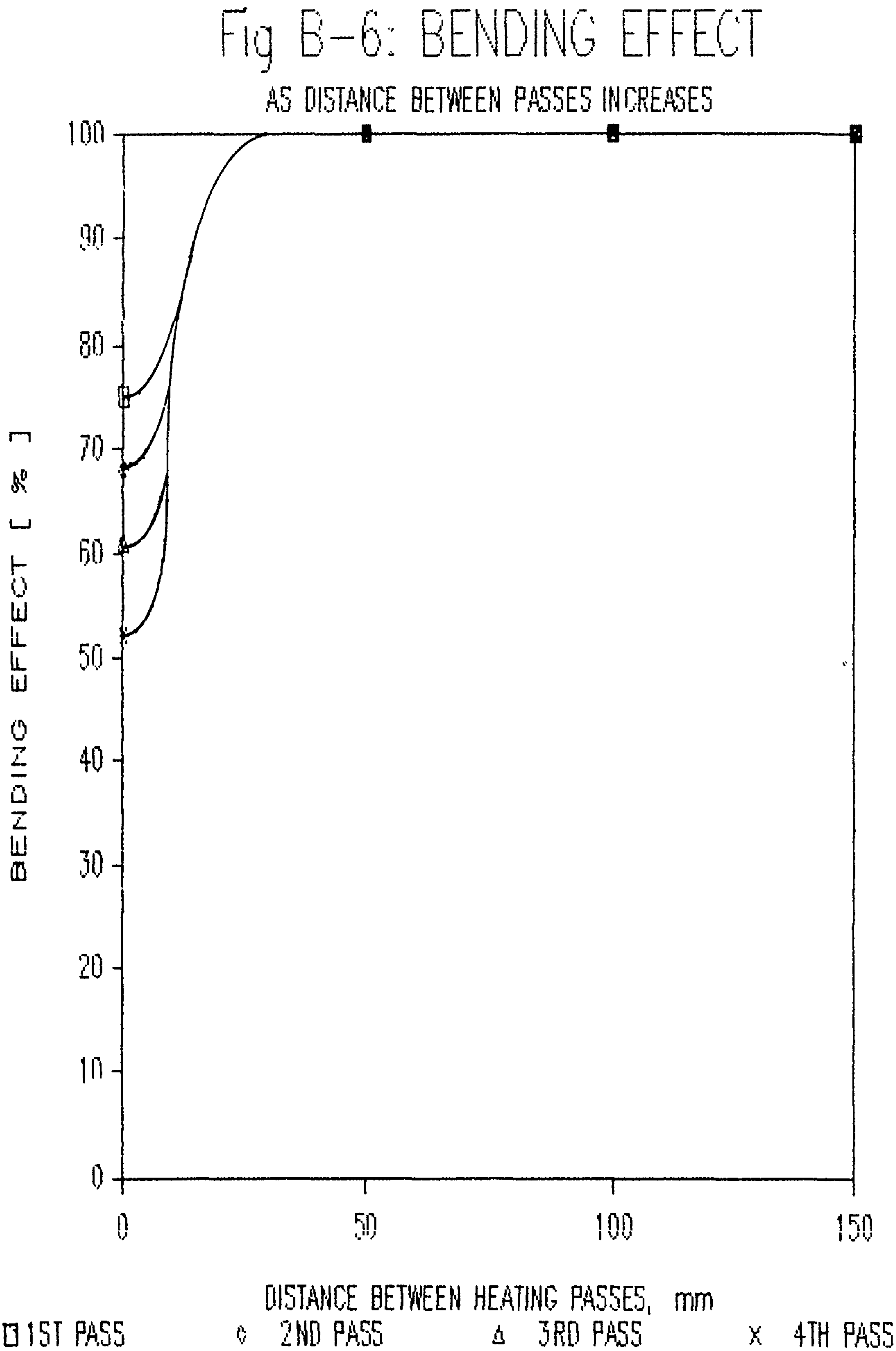


Fig B-6: BENDING EFFECT
AS DISTANCE BETWEEN PASSES INCREASES
BENDING EFFECT [%]
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
DISTANCE BETWEEN HEATING PASSES, mm
1ST PASS
2ND PASS
3RD PASS
4TH PASS

APPENDIX C

FREE-END SAMPLES RECORDED DATA

I. 3/16 INCH THICK FREE-END SAMPLES

A. AFTER WELDING

SAMPLES	H(aw) [inches]	h [inches]	H(aw)-h [inches]	L [inches]	d(w) [radians]	V [volts]	I [amps]	TIME (t) [seconds]
E	0.4353	0.185	0.2503	12.0625	0.02074	21.8	157	62/51 @
F	0.4865	0.185	0.3015	12.0625	0.02497	21.8	158.5	53.5/49.3
G	0.4913	0.185	0.3063	12.0625	0.02537	21.8	157.5	45.4/47.8
H	0.5100	0.185	0.325	12.0000	0.02706	21.8	159	48.0/53.6
I	0.5227	0.185	0.338	12.0000	0.02811	21.8	158.5	47.5/53.5

SAMPLES	Q [cal/cm]	Q/(h*h) [cal/cm*3]
E	757.4	3339.2
F	695.6	3066.8
G	626.7	2762.9
H	693.2	3056.4
I	687.0	3028.8

@ Time to weld side 1/time to weld side 2

NOTE: 1) d(w) = o.5 * arctan [{ H(aw) - h } / (0.5 * L)]

2) Q = [0.75 * 0.24 * V * I * 2] / [v * 3]

B. AFTER THE FIRST FLAME HEATING PASS

SAMPLE	H(a1) [inches]	H(a1) - h [inches]	d(a1) [radians]	d(r1) [radians]	TIME (t) [seconds]	VELOCITY (v1) [in/min]	1/v1 [min/in]
E	0.24183	0.05683	0.004736	0.01600	49.92	14.536	0.0688
F	0.31783	0.13283	0.011068	0.01391	37.02	19.598	0.0510
G	0.3735	0.1885	0.015703	0.00967	25.66	28.205	0.0355
H	0.4652	0.2802	0.023330	0.00373	20.61	34.934	0.0286
I	0.4913	0.3063	0.025506	0.00260	15.40	46.768	0.0214

NOTE: 1) $d(a1) = 0.5 * \arctan [\{ H(a1) - h \} / (0.5 * L)]$

2) $d(r1) = d(w) - d(a1)$

C. AFTER THE SECOND FLAME HEATING PASS

SAMPLE	H(a2) [inches]	H(a2) - h [inches]	d(a2) [radians]	d(r2) [radians]	TIME (t) [seconds]	VELOCITY (v2) [in/min]	1/v2 [min/in]
G	0.28683	0.10183	0.008456	0.00725	25.58	28.294	0.0355
H	0.43483	0.24983	0.020807	0.00252	20.28	35.512	0.0282
I	0.458	0.273	0.022734	0.00277	15.36	46.890	0.0213

NOTE: 1) $d(a2) = 0.5 * \arctan [\{ H(a2) - h \} / (0.5 * L)]$

2) $d(r2) = d(a1) - d(a2)$

3) Samples E and F overcorrected on the second heating pass and measurements were not taken.

D. Determination of average slope for d(r2) versus v relationship.

SAMPLE	d(r2)/d(r1)	(v1 - v2) * 100% / v1
G	0.7494	0.207 %
H	0.677	1.65 %
I	1.064	0.26 %

The average d(r2)/d(r1) was 0.83 or 83%. Therefore, the d(r2) curve in Figure 2-17 has slope of 83% of the d(r1) curve.

I. 1/8 INCH THICK FREE-END SAMPLES

A. AFTER WELDING

SAMPLES	H(aw) [inches]	h [inches]	H(aw)-h [inches]	L [inches]	d(w) [radians]	V [volts]	I [amps]	TIME (t) [seconds]
A	0.426	0.125	0.301	12.0000	0.02506	19	100	43.77
B	0.3648	0.125	0.2398	12.0000	0.01998	19	100	45.00
C	0.3335	0.125	0.2085	12.0000	0.01737	19	100	43.95
D	0.3067	0.125	0.1817	12.0000	0.01513	19	100	43.30
E	0.331	0.125	0.206	12.0000	0.01716	19	100	44.09

SAMPLES	Q [cal/cm]	Q/(h*h) [cal/cm*3]
A	324.18	3215.8
B	345.47	3427.1
C	335.68	3330.0
D	323.90	3213.1
E	329.77	3271.3

NOTE: 1) d(w) = o.5 * arctan [{ H(aw) - h } / (0.5 * L)]

2) Q = [0.75 * 0.24 * V * I * 2] / [v * 3]

B. AFTER THE FIRST FLAME HEATING PASS

SAMPLE	H(a1) [inches]	H(a1) - h [inches]	d(a1) [radians]	d(r1) [radians]	TIME (t) [seconds]	VELOCITY (v1) [in/min]	1/v1 [min/in]
A	0.38233	0.25733	0.021431	0.00363	23.59	30.528	0.0328
B	0.3335	0.2085	0.017368	0.00261	15.31	47.028	0.0213
C	0.30317	0.17817	0.014843	0.00253	17.97	40.078	0.0250
D	0.21167	0.08667	0.007222	0.00791	31.95	19.131 @	0.0523
E	0.30117	0.17617	0.014676	0.00248	15.80	38.699 @	0.0258

@ The line heating path length of samples D and E where 10.1875 inches not 12 inches as in the other samples.

NOTE: 1) $d(a1) = 0.5 * \arctan [\{ H(a1) - h \} / (0.5 * L)]$

2) $d(r1) = d(w) - d(a1)$

C. AFTER THE SECOND FLAME HEATING PASS

SAMPLE	H(a2) [inches]	H(a2) - h [inches]	d(a2) [radians]	d(r2) [radians]	TIME (t) [seconds]	VELOCITY (v2) [in/min]	1/v2 [min/in]
A	0.31883	0.19383	0.016147	0.00528	23.97	30.056	0.0333
B	0.32133	0.19633	0.016355	0.00101	15.49	46.482	0.0215
C	0.293	0.168	0.013996	0.00085	17.98	40.056	0.0250
E	0.2802	0.1552	0.012928	0.00175	15.97	38.287	0.0261

NOTE: 1) $d(a2) = 0.5 * \arctan [\{ H(a2) - h \} / (0.5 * L)]$

2) $d(r2) = d(a1) - d(a2)$

3) Sample D overcorrected on the second heating pass and measurements were not taken.

D. Determination of average slope for d(r2) versus v relationship.

SAMPLE	d(r2)/d(r1)	(v1 - v2) * 100% / v1
A	1.4553	1.545 %
B	0.3884	1.162 %
E	0.7041	1.065 %

The average d(r2)/d(r1) was 0.849 or 84.9%. The d(r2) curve in Figure 2-18 has slope of 80% of the d(r1) curve. Sample C was not used to determine the slope of d(r2) since the angular distortion removed during the second pass of sample C is much lower then that which would be expected.

APPENDIX D

3/16" STIFFENED PLATE OUT-OF-PLANE DEFLECTION READINGS RECORDED AFTER LINE HEATING THE FIRST PASS

Appendix D contains 10 sets of out-of-plane deflection measurements. The 1st set was recorded after welding but prior to any line heating. The rest were taken after each panel was line heated the first time. See Table 2-1 for the 1st pass line heating sequence.

NOTE: In appendixes D, E, F, and G the TRANSVERSE and LONGITUDE spacing is 2 inches. All deflection readings in the matrixes are in .001 inches. For example, the out-of-plane distortion at 10 inches TRANSVERSE and 2 inches LONGITUDE, in the matrix labeled "DISTORTION MEASUREMENTS OF 3/16" PLATE AFTER WELDING" is -0.075 inches (i.e. 0.075 below the reference point). This point is designated D(6,2) as it is on the 6th line in the TRANSVERSE direction and the 2nd line in the LONGITUDE direction.

DISTORTION MEASUREMENTS OF 3/16" PLATE AFTER WELDING

TRANSVERSE

		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	-130	-121	-109	-97	-84	-72	-57	-57	-52	-44	-39	-33	-31	-24	-20	-16	-11	-8	0
	2	-118	-132	-128	-115	-98	-75	-37	-57	-65	-68	-65	-62	-47	-50	-47	-42	-36	-22	14
	4	-110	-130	-134	-125	-107	-75	-33	-56	-73	-81	-79	-67	-40	-57	-63	-61	-50	-26	17
	6	-105	-124	-133	-127	-107	-71	-29	-54	-74	-85	-81	-62	-31	-54	-67	-66	-55	-26	18
	8	-93	-117	-129	-124	-104	-67	-25	-51	-72	-83	-77	-55	-21	-47	-62	-64	-53	-24	19
	10	-89	-112	-123	-120	-100	-64	-22	-48	-68	-79	-72	-48	-12	-38	-54	-56	-47	-20	22
	12	-84	-107	-118	-115	-95	-60	-19	-44	-65	-75	-67	-42	-4	-28	-43	-46	-39	-16	22
	14	-79	-100	-111	-107	-88	-55	-17	-40	-59	-68	-61	-36	2	-21	-34	-38	-32	-12	23
	16	-75	-94	-102	-97	-80	-49	-13	-35	-52	-59	-52	-29	6	-14	-25	-29	-25	-8	24
	18	-71	-87	-92	-84	-68	-43	-12	-28	-42	-48	-43	-23	11	-18	-17	-19	-17	-4	25
	20	-67	-76	-74	-65	-51	-33	-8	-19	-26	-32	-39	-15	14	-2	-9	-10	-10	-2	25
	22	-63	-59	-50	-41	-30	-21	-1	-6	-5	-10	-12	-7	15	0	0	2	-3	1	25
	24	-54	-36	-28	-21	-15	-7	0	9	17	16	7	4	12	7	10	18	7	3	18
	26	-61	-68	-64	-55	-44	-29	-4	-10	-11	-15	-15	-8	19	-6	-14	-18	-22	-14	18
L	28	-67	-81	-83	-76	-61	-38	-5	-21	-29	-33	-28	-12	20	-9	-25	-32	-33	-19	15
O	30	-70	-87	-94	-88	-71	-43	-4	-25	-39	-42	-34	-13	21	-9	-29	-34	-37	-21	14
N	32	-72	-91	-99	-93	-75	-45	-4	-28	-44	-48	-38	-15	21	-11	-32	-41	-40	-24	10
G	34	-75	-93	-103	-97	-78	-46	-5	-33	-49	-54	-42	-16	22	-12	-33	-43	-41	-26	7
I	36	-79	-96	-105	-100	-79	-45	-4	-33	-52	-56	-45	-18	18	-18	-37	-47	-44	-29	5
T	38	-81	-99	-108	-103	-82	-49	-7	-33	-51	-56	-45	-19	16	-18	-39	-49	-47	-32	2
U	40	-84	-102	-110	-104	-84	-52	-8	-32	-50	-55	-46	-23	12	-22	-43	-53	-52	-36	-3
D	42	-88	-104	-109	-102	-84	-54	-12	-33	-49	-54	-46	-25	9	-24	-45	-55	-55	-40	-7
E	44	-92	-101	-99	-88	-73	-50	-16	-33	-43	-46	-41	-26	4	-27	-45	-53	-55	-34	-11
	46	-94	-90	-79	-65	-52	-39	-22	-30	-32	-31	-38	-24	-3	-27	-37	-41	-47	-34	-17
	48	-93	-68	-51	-38	-28	-20	-23	-23	-17	-11	-8	-13	-16	-16	-17	-18	-25	-38	-24
	50	-106	-105	-92	-76	-63	-46	-33	-48	-49	-44	-38	-32	-16	-40	-48	-52	-58	-56	-32
	52	-113	-121	-118	-105	-90	-68	-40	-63	-72	-68	-60	-44	-23	-54	-70	-77	-79	-70	-40
	54	-121	-137	-141	-131	-113	-84	-49	-76	-89	-88	-76	-56	-29	-65	-85	-95	-96	-81	-50
	56	-130	-147	-155	-148	-130	-100	-59	-86	-102	-101	-88	-65	-35	-76	-101	-113	-111	-94	-59
	58	-140	-158	-167	-162	-142	-111	-72	-94	-110	-110	-97	-72	-43	-86	-114	-128	-125	-105	-70
	60	-148	-170	-180	-175	-154	-121	-81	-104	-118	-119	-104	-80	-54	-97	-125	-139	-138	-121	-83
	62	-158	-180	-190	-184	-164	-129	-91	-113	-125	-126	-112	-88	-64	-109	-139	-152	-151	-130	-93
	64	-168	-193	-204	-198	-177	-142	-102	-127	-139	-139	-124	-100	-75	-122	-152	-164	-163	-141	-105
	66	-179	-203	-214	-208	-188	-154	-113	-139	-152	-152	-138	-115	-88	-133	-160	-171	-169	-148	-115
	68	-188	-212	-220	-212	-195	-164	-125	-151	-162	-161	-149	-129	-100	-142	-165	-173	-171	-156	-125
	70	-198	-220	-219	-210	-196	-174	-141	-162	-166	-165	-158	-143	-119	-149	-161	-165	-165	-159	-135
	72	-211	-221	-213	-204	-199	-185	-168	-175	-169	-165	-159	-153	-148	-151	-154	-148	-147	-148	-152

DISTORTION MEASUREMENTS OF 3/16" PLATE AFTER PANEL 5 WAS LINE FLAME HEATED FOR THE FIRST TIME

		TRANSVERSE																		
		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	-138	-131	-118	-107	-95	-84	-68.	-69	-64	-56	-49	-44	-40	-31	-25	-20	-16	-12	0
	2	-128	-143	-141	-130	-115	-91	-54	-74.	-84	-87	-84	-77	-60	-60	-55	-48	-40	-25	13
	4	-124	-143	-150	-143	-126	-95	-54	-81	-102	-112	-107	-90	-57	-69	-73	-68	-56	-31	15
	6	-121	-141	-152	-149	-130	-95	-54	-86	-114	-129	-120	-93	-51	-68	-78	-75	-61	-32	17
	8	-112	-138	-153	-155	-131	-96	-55	-89	-122	-138	-126	-92	-46	-64	-75	-74	-60	-31	18
	10	-110	-136	-152	-152	-134	-97.	-56.	-92	-126	-143	-130	-92	-40	-58	-69.	-68	-55	-28	20
	12	-109	-136	-154	-155	-137	-100	-57.	-93	-128	-145	-131	-89	-39	-52	-63	-62	-50	-25	19
	14	-107	-133	-153	-156	-138	-101	-60.	-91	-124	-141	-127	-87	-35	-50	-59	-58	-47	-23.	19
	16	-105	-132	-151	-154	-138	-102	-61	-86	-114	-130	-117	-81	-34	-48	-56	-54	-43	-21	19
	18	-104	-128	-144	-146	-134	-101	-64	-80	-100	-113	-103	-75	-33	-48	-53	-48	-38	-18	19
	20	-104	-120	-127	-128	-118	-96	-65	-72.	-82.	-91	-86	-67	-34	-45	-47	-41	-33	-17	18
	22	-103	-104	-102	-99	-92	-82	-62	-63.	-65	-68	-67.	-59	-35	-44	-39	-30	-26	-16	15
	24	-97	-83	-78	-78	-74	-69	-64	-55.	-47	-48	-53	-52	-40	-39	-28	-14	-17	-13	9
	26	-107	-117	-118	-108	-97	-85	-70	-72.	-66	-63	-61	-59	-33	-44.	-46	-46	-45	-34	8
L	28	-116	-132	-136	-126	-111	-94	-71	-77.	-73	-69	-64	-57.	-33	-46	-52	-55	-53	-38	4
O	30	-122	-139	-143	-135	-119	-99	-70	-79	-76.	-72	-64	-54	-31	-45	-53	-56	-53	-38	3
N	32	-126	-142	-148	-140	-123	-99	-67	-80	-79	-74	-65	-52	-29	-44	-53	-56	-54	-38.	1
G	34	-129	-144	-151	-143	-125	-99	-66	-84	-83	-78	-67	-51	-27	-43	-52	-55	-53	-38	-1
I	36	-133	-146	-153	-145	-126	-96	-64.	-85	-84	-80	-68.	-52.	-29	-46.	-54	-56.	-53	-38.	0
T	38	-133	-149	-156	-147	-127	-99	-64	-81	-82	-78	-68	-52	-29	-45	-54	-56	-53	-37.	0
U	40	-134	-151	-157	-148	-128	-100	-64	-77.	-80	-77	-68.	-55	-29	-46.	-56	-59	-56	-39	0
D	42	-136	-151	-156	-146	-126	-100	-66	-77	-79	-76	-69	-58.	-29	-46	-56	-61	-58	-40	1
E	44	-135	-146	-145	-132	-114	-94	-68	-75	-73	-69	-65	-60	-30	-45	-54	-57	-56	-39	3
	46	-134	-133	-123	-107	-95	-83	-70	-71	-63.	-58	-54	-55	-32	-42	-45	-45	-44	-34	4
	48	-129	-105	-90	-80	-71	-64	-66.	-65	-56.	-47	-40	-40	-38	-31.	-25.	-18	-17.	-21	4
	50	-135	-135	-126	-117	-105	-89	-71	-81	-78	-72.	-61	-48.	-31.	-52	-54	-49	-44	-33	2
	52	-138	-148	-150	-145	-130	-105	-73	-94	-100	-96	-79	-56	-32	-62.	-75	-74	-62	-41	-1
	54	-142	-161	-170	-167	-148	-116	-76	-105	-118	-116	-96	-63	-31.	-66	-86	-87	-74	-47.	-5
	56	-157	-167	-160	-179	-158	-123	-80	-112	-131	-130	-106	-68	-31	-69	-91.	-96	-82	-53.	-9
	58	-154	-175	-187	-184	-162	-127	-89	-115	-136	-136	-111	-71	-32	-70	-93.	-99	-87	-56	-13
	60	-159	-181	-193	-188	-166	-129	-89	-117	-137	-136	-112	-71	-35	-72	-94	-101	-90	-61	-19
	62	-166	-186	-197	-191	-168	-132	-92	-119	-136	-136	-111	-72	-38	-75	-98	-105	-96	-67	-24
	64	-173	-195	-205	-198	-175	-139	-96	-123	-138	-136	-114	-77	-42	-80	-103	-109	-100	-71	-30
	66	-180	-202	-210	-203	-181	-144	-101	-127	-140	-137	-114	-82	-46	-85	-105	-110	-101	-73	-35
	68	-187	-207	-212	-202	-182	-149	-107	-130	-139	-135	-116	-88	-52	-88	-103	-106	-98	-76	-40
	70	-193	-211	-208	-195	-178	-153	-116	-133	-133	-127	-114	-93	-63	-88	-95	-92	-86	-73.	-43.
	72	-202	-209	-197	-184	-174	-157	-135	-137	-129	-118	-107	-96	-86	-81	-76	-65.	-60.	-55	-53

DISTORTION MEASUREMENTS OF 3/16" PLATE AFTER PANELS 5 AND 4 WERE LINE HEATED FOR THE FIRST TIME

TRANSVERSE

		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	85	81	81.5	80	80	79	83	70	63	57.5	51.5	45	37	32	26	18	10	0	0
	2	82	55	47	47	51	65	92	59	40	24	18	11	16	4	-2	-5	-9	-4	21.5
	4	72	43	25	21	30	53	86	50	22	0	-6	-1.5	19	-4	-17	-21	-18	-2	31.5
	6	61	33	10	4	17	45	79	41	8	-16	-18	-4.5	24	-3	-20	-23	-18	4	41
	8	57	24	-1	-6	7	38	72	33	-2	-26.	-25	-4	30	4	-14	-19	-12	13	50
	10	46	15	-9	-15	-2	29	64	25	-10	-34	-30	-5	36	11	-6	-9	-2	22	59
	12	35	5	-17	-22	-9	21	57	18	-18	-40	-33	-4	40	19	4	2	8	30	67
	14	22	-2	-20	-25	-12.	15	48	13	-21	-41	-34	-3	42.5	24	11	10	17	38	75
	16	12	-9	-22	-25	-13.	10	42	10	-18	-36	-29	1.5	44	28	18	18	25	45	82.5
	18	-1	-15	-22	-20	-11	6	36	10	-11	-25	-20	5	46	31	25	25	35	54	89
	20	-14	-19	-18	-14	-7.5	4	26	13	2.5	-7	-3	14.5	47	36	33	38	45	60	95
	22	-23	-18	-11	-6	0	8	23	21	20	15	14	23	47.5	39	44	53	57	67	99
	24	-24	-11	-2.5	0	6	12	8	26	35	34	30	32	44	46.5	57	73	70	76	98
	26	-41	-65	-60	-46	-26	-5	11	7	15	29	23	26	53	43.5	42.5	44	48	61	103
L	28	-52	-80	-114	-106	-79	-36	10	4	8	13	21	30	56.5	44.5	40	39	44	61	104
O	30	-57	-90	-113	-111	-89	-45	13.5	4	7.5	13	23	37	62	49	43	42	47	65	107
N	32	-59	-69	-57	-37	-20	-5	20	7	8.5	14	26	42	67	53	46	45	49	68	108
G	34	-59	-45	0	33	46	39	25	7	9	14.5	28	47	73	57.5	50	49	54	72	110
I	36	-55	-39	10	45	58	55	33	13	14	18	31	50	76	58	52	51	57	74	113.
T	38	-45	-52	-31	-5	17	30	39	21	22.5	25	37	55	80	63	55	55	60	78	116
U	40	-34	-60	-68	-53	-26	5	47	33	30	31	41	57	84	64	57	55	60	78	117.
D	42	-22	-51	-58.	-45	-18	13	54	40	37	38	45	58	89	71	61	57	61	80	120
E	44	-5	-25	-21	-5	15	37	61	52	52	53	57	63.5	94	76	67	64	65	82	122
	46	15	7	21	38	51	64	70	67	72	75	78	76	98	84	80	80	79	88	124
	48	38	57	70	78	85	90	85	83	88	95	99	96	96	102	105	109	108	102	123
	50	54	58	67	73	82	88	97	82	79	80	87	95	110	88	82	81	83	90	123
	52	76	70	71	74	82	92	111	83	69	66	75	94	117	84	78	63	68	83	119
	54	97	81	75	74	84	99	124	86	65	57	69	95	125	85	63	54	59	77	114
	56	119	97	84	79	89	107	138	97	69	59	72	100	130	89	61	50	54	72	108
	58	137	112	95	87	98	119	148	111	81	69	81	108	137	93	63	50	51	68	102
	60	159	128	106	98	110	132	163	126	97	84	95	118	143	96	65	50	49	63	93
	62	178	146	122	113	125	147	177	141	113	100	103	128	147	99	65	48	45	57	86
	64	198	161	137	127	137	158	190	150	124	111	117	133	151.	99	66	46	41	53	78
	66	219	179	154	143	152	171	203	161	133	121	124	137	155	100	65	47	41	49	71
	68	238	200	176	166	172	187	213	172	147	132	133	142	158	104	71	53	44	46	63
	70	257	222	205	198	197	202	221	185	164	150	145	145	155	110	84	73	56	47	53
	72	275	249	243	233	223	218	220	196	184	172	162	152	142	123	107	97	81	64	45

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 4, AND 2 WERE LINE HEATED THE FIRST TIME

		TRANSVERSE																		
		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	205	181	157	133	109	85	66	37	16	2	-7	-13	-16	-13	-11.	-9	-8	-7	0
	2	191	146	115	96	80	72	71	13	-14	-34	-44	-56	-43	-42.	-39	-35	-31	-20	15
	4	171	124	87	68	58	57	63	3.5	-35	-61	-71	-71	-45	-52.	-55	-53	-45	-23	19
	6	149	104	65	47	41	44	52	-5	-49	-77	-84	-75	-42	-55	-62	-59	-49	-23	22
	8	133	86	49	30	25	30	42	-9	-54	-80	-84	-72	-38.	-53	-61	-59	-48	-20	25
	10	112	68	32	15	9	16	30	-15	-53	-75	-78	-68.	-35	-50	-57	-53	-42	-16	27
	12	90	50	17	0	-4	3	20	-18	-50	-69	-72	-64	-33	-44	-48	-44	-34	-11	30
	14	69	34	3	-11	-14	-8	7	-20	-46.	-62	-64	-60	-32.	-40	-42.	-37	-28	-6.5	33
	16	49	18	-7	-19	-22	-17	-3	-26	-46	-58	-60	-57	-31.	-36.	-36	-30	-22	-2	37
	18	29	3	-16	-24	-27	-25	-13	-31	-46.	-56	-59	-55	-30.	-34	-31	-24	-15	3	41
	20	9	-9	-20	-26	-29	-30	-25	-34	-44	-54	-56	-52	-30	-30.	-26	-18	-10	7	43
	22	-8	-14	-20	-24	-28	-31	-30	-31	-36	-46	-52	-51	-29	-31	-22	-9	-3	10	44
	24	-15	-12	-16	-24	-28	-33	-34	-32	-28	-33	-41	-43	-31	-27	-13	6	7	17	42
	26	-38	-73	-79	-76	-66	-53	-42	-49	-48	-50	-49	-48	-21	-31	-32	-27	-19	-1	45
L	28	-56	-103	-141	-142	-125	-87	-43	-54	-55	-56	-51	-43	-17	-30	-36	-34	-26	-2	45
O	30	-67	-110	-145	-152	-136	-96	-40	-54	-58	-58	-50	-36	-11	-25	-32.	-32	-23	1	47
N	32	-75	-94	-92	-78	-66	-55	-34	-53	-60	-59	-48	-31	-5	-19	-28	-28	-20	3	47.5
G	34	-80	-74	-36	-8	0	-9	-29	-53	-60	-59	-46	-26	2	-14	-22	-22	-15	7	48
I	36	-82.	-73	-29	3	14	6	-22	-49	-55	-55	-42	-21	6	-11.	-18	-18	-11	9	51
T	38	-79	-90	-74	-48	-30	-21	-17	-38	-45	-45	-34	-15	11	-5	-13	-13	-7	12	52
U	40	-73	-102	-114	-100	-77	-50	-11	-27	-34.	-36	-28	-12	11	-2	-11	-12	-7	12	51.5
D	42	-67	-97	-107	-96	-73	-45	-5	-20	-26	-28	-22	-10	21	3	-7	-10	-6	13	53
E	44	-56	-76	-74	-62	-43	-24	0	-9	-11	-11	-8	-4	26	8	-1	-3	-2	14	54
	46	-41	-50	-34	-22	-9	1	8	5	9	11	12	9	30	17	12	12	11	20	55
	48	-22	-3	9	17	23	26	21	18	23	28.5	32	29	28	33	36	41	39	32	53.5
	50	-11	-9	-1	6.5	14	22	30	14	12	12	18.5	26	40	19	13	12	13	19	49
	52	6	-1	0	3	12	24	42	14	0	-3	6	24	46	15	-2	-7	-3	11	45
	54	23	6	-1	0	10	28	53	16	-6	-12	0	24	53	16	-7	-16	-12	5	40
	56	40	19	4	2	13	35	65	26	-2	-11	1	28	59	19	-9	-21	-18	-1	33
	58	54	30	12	8	20	43	72	38	8	-2	10	36	65	22	-8	-22	-22	-5	27.5
	60	72	42	21	16	29	54	85	50	24	12	22	44	69	25	-6	-22	-24	-11	19
	62	87	56	34	28	40	66	96.5	63	38	27	34	53	72	26	-7	-25	-29	-17	12
	64	102	68	44	38	49.5	75	107	71	47	37	42	58	76	25	-7	-28	-33	-22	4
	66	119	82	58	52	62	85	112	79	55	44	47	60	78	25	-9	-27	-33	-25	-3
	68	135	99	78	72	78	98	126	87.5	66	54	54	63	79	27.5	-4	-22	-31	-29	-11
	70	151	117	103	100	101	110	131	97.5	81	69	64	65	75	32	-8	-8	-20	-28	-17
	72	163	141	136	131	123	123	126	106	95	85	78	70	61	44	29	19	5	-11	-30

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 4, 2, AND 8 WERE LINE HEATED THE FIRST TIME

TRANSVERSE

		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	183	161	139	116	94	71	53	25	6	-6	-14.	-19	-22	-19	-16.	-13	-10	-10	0
	2	171	127	98	80	66	59	59	2	-23	-41.	-51.	-62	-49	-48	-44	-40	-34.	-22.	14
	4	152	106	72	53	45.5	45	51.5	-7	-43	-67	-76	-77	-50	-58	-60	-57	-49	-26.	17
	6	132	88	51	34	29	32	41	-14	-56	-82	-89	-79.	-47.	-61	-67	-63.	-53	-26	19
	8	117	71	35	17	13	20	31.5	-19	-61	-86	-89	-77	-44	-59	-67	-63.	-52	-24	22
	10	98	54	20	2	-1.5	6	21	-24	-59	-81	-84	-73	-41	-55	-62	-58	-46	-20	25
	12	77	36	4	-11	-14	-6	11	-27	-56.	-74.	-77	-69	-39	-50	-54	-50	-39	-16	26.5
	14	58	22	-7	-21	-23	-16	-1	-28	-53	-68	-71	-66	-38	-46.	-48	-43	-33	-12	29
	16	39	7	-16	-27.	-29.	-24.	-11	-33.	-52.	-64	-67	-62.	-37	-43	-42	-36	-27.	-7	32
	18	21	-5	-24	-32	-33	-31	-19	-38.	-53	-62	-65	-61	-36	-41	-38	-30	-21.	-2.5	35
	20	3	-16	-26.	-32	-34.	-36	-31	-40	-51	-60	-62	-58	-35.	-37.	-33	-25	-17	1	38
	22	-12	-19	-24	-29.	-33	-37	-36	-38	-43	-52.	-58	-57	-35	-38.	-29	-16	-9.5	4	39
	24	-17	-15	-19	-28.	-33	-38	-40	-39	-35	-41	-49	-50	-38.	-34	-20	0	0.5	11	37
	26	-39	-73	-82	-78	-69	-57	-47	-55	-54.	-57	-57	-55	-29	-39	-40	-34	-25	-6	40
L	28	-54	-102	-140	-143	-126	-90	-48	-60	-63	-65	-61	-52	-25	-37.	-44	-42	-32	-7.5	40
O	30	-63	-107	-143	-152	-137	-99	-44.	-61.	-69	-70	-62	-47	-20	-34	-41	-40	-30	-5	42
N	32	-69	-89	-87	-77	-65	-56	-38	-61.	-72	-74	-62.	-42.	-15	-29	-37	-36.	-27	-3	42.5
G	34	-71	-67	-31	-4	3	-10	-34	-63.	-76	-77	-63	-39	-8.5	-24	-31.	-31	-22	0	43.5
I	36	-71	-63	-23	7	16	5	-27	-59	-72	-75	-61	-36	-6	-23.	-30	-28.	-20	3	46
T	38	-64	-80	-68	-48	-30	-22	-22	-48	-61	-66	-53	-30	-1.5	-19	-27	-25.	-17	5.5	47.5
U	40	-56	-92	-111	-102	-80	-52	-15	-37	-49	-54	-46	-27.	1.5	-17	-26.	-26.	-18	5.5	48
D	42	-47	-84	-104	-99	-77	-50	-10	-28.	-39	-43	-38	-25	6	-13.	-25	-26	-18	6.5	49.5
E	44	-34	-61	-66	-62	-47	-28	-5	-17	-23	-26.	-25	-20	10	-10	-20	-20	-14	8	51
	46	-17	-30.	-24	-18	-10	-2	2	-3.5	-3.5	-6	-5	-8	13	-2	-6	-2	1	14	52
	48	6	17	24	25	26	25	15	8	11	13.5	15	11.5	11	17	22	30	30	27	51
	50	19	16	18	21	24	26	27	15	14	12.5	15	16.5	22.5	8	6	7	7	16	49
	52	40	27	22	23	28	32	38	24	18	14	15.5	20	28	6	-4.5	-8	-4.5	10	45
	54	61	38	27	25	30	38	52	33.5	24	18	19	25	35	7.5	-8	-13.	-10	6	41
	56	82	55	38	33	38	48	67	47	34	27	27	32	42.5	10	-9.5	-17	-14	2	37
	58	101	71.5	52	45	49	60	77	63	47	38	37	41	49	13	-9.5	-19	-17	-1	33
	60	125	88	66	59	63	75	92	76	60	50	47.5	50	55	16	-8.5	-20	-20	-5	27
	62	146	109	85	75	79	91	106	90	71	60	57	59	60	19	-9.5	-24	-25	-9	23
	64	168	126	100	89	92	103	119	97	77	64.5	61.5	65	65	21	-10	-25	-27	-11	18
	66	191	146	118	106	107	116	132	102	81	67	63.5	66	70	24.5	-6	-22	-25	-11	14.5
	68	215	168	140	128	126	132	143	109	89	73	67	69	74.5	31	2.5	-12	-19	-11	11.5
	70	239	194	170	156	147	146	151	117	98	82	73	70	73.5	39	19	5.5	-4	-6	9
	72	260	225	207.	189	169	158	151	121	107	91	80	72	65	52	41	36	26	14.5	0.5

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 4, 2, 8, AND 6 WERE LINE HEATED THE FIRST TIME

		TRANSVERSE																		
		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	-20	-33	-44	-56	-66	-77.	-83	-101	-109	-110	-107	-101	-92	-76	-62	-49	-35	-21	0
	2	-20	-55	-74	-83	-87.	-85	-73	-119	-135	-144	-146	-146	-122	-109	-96	-80	-62	-38	7
	4	-25	-63	-90	-100	-102	-93	-77	-123	-151	-168	-171	-163	-127	-125	-117	-101	-81	-47	4
	6	-32.	-68	-98	-111	-111	-100	-82	-126	-162	-182	-183	-166	-127	-130	-127	-114	-90	-53	0
	8	-33	-73	-104	-118	-118	-106	-87	-128	-166	-186	-185	-167	-127	-133	-131	-119	-95	-57	-3
	10	-40	-78	-109	-123	-123	-112	-92	-131	-163	-181	-181	-166	-127	-134	-131	-118	-95	-59	-7
	12	-48	-85	-114	-127	-128	-117	-98	-131	-160	-176	-175	-163	-128	-132	-128	-116	-95	-60	-11
	14	-54.	-88	-115	-127	-128	-119	-103	-129	-156	-170	-171	-162	-129	-131	-127	-114	-94	-62.	-16
	16	-60	-92	-114	-125	-126	-121	-108	-132	-154	-167	-168	-160	-130	-131	-123	-110	-91.	-64	-20
	18	-67	-93	-112	-120	-123	-121	-111	-133	-152	-165	-167	-159	-131	-130	-120	-106	-89	-65	-25
	20	-73	-93	-104	-111	-116	-118	-116	-130	-144	-158	-161	-156	-130	-127	-117	-102	-87	-67	-30
	22	-76	-86	-93	-101	-107	-114	-115	-120	-128	-143	-151	-152	-129	-129	-115	-99	-87	-70	-35
	24	-72.	-73	-81	-93	-101	-110	-114	-116	-116	-125	-136	-138	-130	-127	-111	-91	-87	-74	-43.
	26	-83	-120	-132	-133	-129	-121	-114	-125	-127	-132	-135	-137	-116	-122	-120	-114	-107	-94	-43
L	28	-89	-138	-179	-188	-178	-146	-108	-123	-128	-131	-130	-127	-107	-115	-118	-116	-108	-92	-43.
O	30	-89	-135	-173	-187	-178	-147	-98	-116	-124	-127	-122	-115	-95	-103	-111	-110	-102	-85	-40
N	32	-86	-109	-111	-107	-104	-100	-84	-118	-118	-121	-114	-102	-82	-91	-99	-100	-94	-77	-35
G	34	-80	-81	-49	-30	-28	-45	-71	-101	-112	-115	-105	-89	-68	-77	-86	-87	-82	-67	-27
I	36	-72	-70	-37	-13	-9	-23	-56	-88	-99	-103	-93	-77	-57	-67	-74	-75	-70	-55	-16
T	38	-57	-77.	-72	-57	-46	-42	-43	-68	-80	-86	-78	-63	-45	-54	-61	-63	-58.	-44	-4
U	40	-42.	-79	-102	-100	-85	-63	-28	-49	-62	-68	-63	-52	-31	-44	-52	-54	-49	-33	8
D	42	-27	-66	-87	-87	-73	-51	-14	-33	-45	-51	-49	-41	-16	-31	-40	-42	-36	-19	24
E	44	-7	-36	-44	-44	-34	-19	1	-14	-21	-27	-27	-25	0	-20	-26	-25	-20	-2	42
	46	18	0	4	7	11	17	18	9	7	5	3	-1	16	-2	-4	-2	2	16.5	61.5
	48	42	52	56	55	53	50	39	30	30	31.5	31	26	25	32	37.5	47	51	51	79
	50	60	53	56	57	58	59	59	44.5	40.5	38	40	43	50	42	44	50	55	66.5	100
	52	85	69	67	67	71	74	80	62.5	53	47.5	50.5	58	71	56	54	59	67	82.5	119
	54	109.	85.5	77.5	77	83	90.5	104	82	70	63	67	78	95	74	68	71	80	100	138
	56	135.	108	96	93	99	109	130	109	95	89	92	103	120	94	83	84	95	118	157
	58	158.	130	116	112	118	130.	150	138	124	117	120	130	144	114	101	101	111	135	176
	60	185	153	137	132	140	155	177	166	152	147	150	157	168	136	121	119	129	152.	193
	62	209.	177	160	155	164	179.	201.	192	181	175	177	185	193	158	139.	136	145	171	212
	64	235	199	181	176	183.	200	226	211	201	196	199	208	217	180	160	156	164	190	229
	66	261	223	204	199	206	224	251	230	219	214	217	227	240	204	184	180.	188	212	247
	68	287	249.	233	228	235	249	272	250	239	234	236	247	263	230	214	210	216	232	266
	70	314	278	267.	264	266	274	292.	270	261	256	258	266	282	257	248	248	249	259	286
	72	337	314	310	305	296.	297	303	286	281	280	282	286	293	291	292	300	302	302	301

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 4, 2, 8, 6, AND 1 WERE LINE HEATED THE FIRST TIME

TRANSVERSE

		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	-25	-45	-61	-78	-91.	-103	-109	-125	-131	-131	-125	-117	-104	-87.	-72	-55	-39	-23	0
	2	-50			-123			-116			-179			-152	-139	-121	-102	-83	-56	-8
	4	-82			-155			-139			-217			-173	-169	-138	-141	-118	-81	-26.
	6	-114			-182			-163			-245			-191	-192	-186	-169	-143	-101	-45
	8	-138			-208			-185			-265			-207	-211	-207	-190	-163	-121	-64
	10	-168			-232			-209			-278			-224	-228	-223	-206	-180	-138	-82
	12	-197	-227	-247	-254	-252	-242	-232	-256	-278	-291	-290	-277	-240	-241	-236	-219	-195	-156	-103
	14	-223			-271			-255			-305			-257	-257	-249	-232	-210	-174	-124
	16	-246			-285			-276			-319			-274	-271	-261	-244	-223	-191	-143
	18	-268			-296			-295			-334			-291	-287	-274	-255	236	-207	-163
	20	-289			-303			-316			-344			-307	-300	-287	-268	-251	-225	-184
	22	-305			-311			-328			-346			-322	-317	-301	-280	-265	-244	-206
	24	-309	-310	-317	-328	-334	-339	-342	-340	-336	-340	-348	-347	-336	-328	-310	-284	-277	-259	-227
	26	-332			-382			-359			-366			-339	-342	-336	-326	-317	-299	-246
L	28	-350			-458			-367			-381			-346	-350	-350	-344	-333	-314	-263
O	30	-362			-474			-370			-392			-350	-354	-358	-353	-343	-323	-275
N	32	-372			-400			-371			-402			-353	-358	-363	-360	-351	-332	-287
G	34	-380			-331			-372			-411			-354	-360	-365	-363	-356	-338	-296
I	36	-386	-382	-348	-324	-321	-337	-370	-402	-413	-414	-401	-381	-359	-367	-370	-369	-361	-343	-302
T	38	-385			-382			-371			-410			-361	-368	-374	-373	-366	-347	-307
U	40	-384			-440			-370			-406			-363	-374	-381	-380	-372	-353	-312
D	42	-382			-442			-370			-403			-364	-378	-385	-384	-376	-357	-314
E	44	-376			-413			-369			-393			-364	-382	-388	-384	-376	-358	-313
	46	-368			-377			-366			-377			-364	-381	-382	-376	-371	355	-311
	48	-354	-344	-340	-342	-343	-346	-357	-365	-364	-363	-361	-367	-367	-360	-353	-342	-337	-337	-308
	50	-350			-352			-350			-370			-356			-353			-304
	52	-339			-356			-343			-374			-349			-361			-300
	54	-328			-359			-334			-373			-341			-364			-297
	56	-317			-358			-323			-363			-332			-366			-295
	58	-308			-354			-316			-349			-322			-366			-293
	60	-295	-325	-344	-347	-340	-324	-304	-315	-328	-334	-332	-325	-314	-345	-362	-364	-355	-331	-292
	62	-284			-338			-293			-321			-306			-362			-290
	64	-272			-332			-283			-316			-296			-359			-288
	66	-260			-323			-274			-312			-288			-350			-287
	68	-247			-308			-265			-307			-280			-337			-284
	70	-235			-286			-261			-289			-277			-316			-281
	72	-224	-249	-254	-260	-268	-269	-264	-283	-288	-291	-290	-288	-283	-284	-286	-280	-280	-280	-284

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 4, 2, 8, 6, 1, AND 7 WERE HEATED THE FIRST TIME

		TRANSVERSE																		
		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	-19	-41	-57	-73	-87	-99	-105	-122	-128	-128	-123	-114	-104	-87.	-71.	-55	-37	-23	0
	2	-44			-119			-113			-177			-150			-101			-3
	4	-75			-151			-137			-214			-172			-140			-26
	6	-108			-178			-160			-243			-190			-167			-45.
	8	-133			-204			-182			-263			-206			-189			-63.
	10	-162			-228			-206			-276			-222			-205			-82
	12	-190	-222	-241	-250	-248	-239	-229	-254	-276	-289	-288	-276	-239	-241	-234	-218	-192	-155	-103
	14	-216			-267			-252			-302			-255			-231			-123
	16	-240			-281			-272			-317			-273			-243			-142
	18	-262			-292			-292			-333			-289			-255			-162
	20	-282			-299			-314			-343			-305			-267			-184
	22	-298			-306			-323			-344			-321			-279			-205
	24	-303	-305	-314	-325	-331	-337	-339	-338	-334	-339	-346	-346	-335	-326	-308	-283	-276	-259	-227
	26	-327			-376			-356			-366			-337			-325			-245
L	28	-344			-453			-364			-380			-345			-343			-262
O	30	-355			-469			-368			-391			-349			-352			-274
N	32	-365			-395			-369			-400			-352			-359			-286
G	34	-373			-327			-370			-409			-353			-362			-295
I	36	-378	-375	-343	-319	-319	-336	-371	-401	-411	-412	-400	-381	-357	-365	-370	-367	-359	-341	-301
T	38	-378			-379			-371			-408			-360			-370			-305
U	40	-377			-440			-369			-405			-362			-377			-311
D	42	-376			-442			-369			-402			-362			-382			-312
E	44	-371			-412			-368			-392			-362			-382			-312
	46	-364			-375			-366			-376			-362			-374			-309
	48	-350	-343	-339	-342	-343	-346	-357	-364	-363	-361	-360	-365	-366	-358	-351	-340	-336	-336	-307
	50	-347			-337			-348			-368			-352			-352			-303
	52	-336			-334			-340			-373			-345			-360			-301
	54	-324			-334			-330			-372			-336			-363			-299
	56	-310			-329			-318			-361			-327			-366			-297
	58	-296			-322			-310			-344			-317			-366			-296
	60	-278	-298	-310	-312	-308	-300	-295	-305	-318	-325	-324	-317	-307	-342	-360	-364	-356	-334	-297
	62	-261			-299			-281			-310			-298			-363			-295
	64	-243			-288			-270			-301			-290			-359			-296
	66	-224			-273			-256			-297			-280			-351			-295
	68	-203			-257			-244			-290			-272			-338			-295
	70	-181			-238			-236			-280			-268			-316			-293
	72	-162	-195	-208	-220	-233	-237	-235	-256	-264	-271	-273	-274	-273	-280	-284	-282	-286	-290	-297

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 4, 2, 8, 6, 1, 7, AND 3 WERE HEATED THE FIRST TIME

		TRANSVERSE																		
		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	-16	-38	-55	-73	-87	-101	-107	-124	-132	-132	-128	-121	-113	-97	-80	-63	-45	-27	0
	2	-41			-119			-117			-181			-161			-102			-22
	4	-72			-150			-139			-217			-184			-137			-61
	6	-104			-177			-163			-246			-203			-166			-65
	8	-127			-204			-186			-266			-221			-189			-88
	10	-157			-228			-209			-283			-239			-207			-111
	12	-184	-217	-240	-250	-250	-242	-233	-259	-284	-298	-299	-290	-257	-246	-237	-222	-203	-176	-136
	14	-210			-267			-257			-313			-276			-237			-157
	16	-235			-280			-278			-329			-294			-251			-178
	18	-256			-292			-297			-344			-311			-266			-199
	20	-276			-298			-319			-355			-327			-283			-220
	22	-292			-306			-330			-357			-341			-300			-238
	24	-297	-300	-310	-324	-332	-339	-345	-345	-344	-353	-361	-364	-355	-350	-333	-311	-304	-288	-258
	26	-321			-378			-362			-380			-357			-345			-274
L	28	-338			-455			-371			-395			-362			-360			-287
O	30	-351			-459			-374			-405			-365			-368			-297
N	32	-362			-394			-375			-414			-366			-373			-306
G	34	-371			-326			-376			-421			-366			-375			-312
I	36	-377	-374	-343	-321	-321	-339	-374	-407	-419	-422	-410	-391	-368	-375	-380	-379	-372	-355	-315
T	38	-377			-382			-375			-416			-369			-381			-317
U	40	-377			-442			-374			-410			-369			-386			-320
D	42	-376			-444			-373			-407			-367			-387			-318
E	44	-372			-413			-371			-395			-366			-385			-316
	46	-365			-377			-368			-377			-364			-376			-310
	48	-353	-354	-341	-343	-344	-348	-359	-366	-364	-362	-360	-365	-366	-358	-351	-341	-336	-334	-305
	50	-351			-340			-349			-369			-352			-351			-299
	52	-341			-338			-341			-373			-343			-356			-295
	54	-329			-337			-330			-370			-333			-357			-290
	56	-315			-333			-318			-358			-322			-358			-286
	58	-303			-326			-309			-341			-316			-355			-282
	60	-285	-305	-315	-316	-311	-302	-294	-303	-315	-321	-318	-310	-299	-332	-349	-353	-343	-319	-280
	62	-268			-303			-280			-303			-288			-349			-275
	64	-251			-292			-266			-294			-277			-343			-274
	66	-233			-277			-254			-288			-267			-332			-271
	68	-213			-261			-242			-280			-257			-317			-268
	70	-191			-241			-231			-270			-252			-293			-264
	72	-171	-203	-214	-224	-234	-236	-230	-249	-256	-260	-260	-258	-256	-256	-256	-256	-266	-261	-265

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 4, 2, 8, 6, 1, 7, 3, AND 9 WERE HEATED THE FIRST TIME

		TRANSVERSE																		
		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	-60	-80	-95	-110	-122	-133	-137	-152	-157	-154	-149	-140	-130	-110	-91	-72	-51	-31	0
	2	-84			-155			-145			-204			-176			-111			-18
	4	-115			-186			-168			-240			-201			-147			-44
	6	-145			-213			-192			-269			-221			-175			-69
	8	-167			-238			-205			-290			-239			-200			-94
	10	-195			-261			-238			-306			-257			-220			-118
	12	-222	-252	-273	-282	-280	-272	-261	-286	-309	-322	-321	-310	-276	-262	-252	-236	-216	-187	-144
	14	-247			-299			-285			-347			-295			-251			-167
	16	-269			-311			-306			-353			-314			-266			-190
	18	-290			-321			-324			-369			-331			-283			-211
	20	-308			-328			-345			-379			-348			-301			-233
	22	-323			-335			-356			-381			-363			-318			-253
	24	-327	-331	-342	-352	-360	-367	-371	-373	-371	-376	-387	-390	-377	-371	-354	-330	-323	-306	-273
	26	-348			-406			-388			-404			-380			-365			-291
L	28	-365			-481			-397			-420			-386			-381			-306
O	30	-376			-493			-400			-430			-389			-390			-317
N	32	-386			-419			-400			-439			-391			-396			-326
G	34	-393			-349			-401			-446			-392			-399			-334
I	36	-398	-396	-366	-345	-345	-362	-398	-432	-445	-448	-437	-419	-395	-402	-406	-403	-396	-378	-338
T	38	-397			-406			-399			-443			-396			-406			-341
U	40	-396			-463			-397			-438			-397			-411			-345
D	42	-394			-464			-396			-436			-396			-413			-345
E	44	-388			-432			-394			-424			-395			-412			-344
	46	-381			-395			-389			-405			-394			-405			-341
	48	-367	-360	-358	-361	-363	-367	-380	-389	-389	-388	-388	-394	-397	-391	-384	-373	-368	-366	-338
	50	-364			-356			-369			-394			-381			-366			-333
	52	-352			-353			-361			-398			-373			-363			-329
	54	-340			-351			-349			-395			-362			-359			-326
	56	-327			-346			-335			-381			-350			-357			-321
	58	-313			-338			-326			-360			-337			-355			-315
	60	-296	-316	-327	-328	-324	-316	-310	-318	-331	-337	-335	-331	-325	-341	-350	-351	-348	-337	-310
	62	-278			-315			-295			-317			-313			-349			-303
	64	-260			-303			-280			-307			-300			-343			-296
	66	-241			-288			-267			-300			-287			-332			-288
	68	-221			-270			-253			-290			-274			-316			-279
	70	-200			-250			-241			-280			-266			-296			-269
	72	-179	-211	-221	-231	-243	-244	-239	-258	-265	-268	-268	-268	-266	-271	-271	-266	-264	-262	-260

APPENDIX E

3/16" STIFFENED PLATE OUT-OF-PLANE DEFLECTION READINGS RECORDED AFTER LINE HEATING THE 2ND PASS

Appendix E contains 9 sets of out-of-plane deflection measurements. The 1st set was recorded prior to any 2nd pass line heating. The rest were taken after each panel was line heated the 2nd time. Panel # 4 was not heated a second time. This panel had excessive buckling and a 2nd line heating pass would provide no useful data. See Table 2-1 for the 2nd pass line heating sequence.

NOTE: In appendixes D, E, F, and G the TRANSVERSE and LONGITUDE spacing is 2 inches. All deflection readings in the matrixes are in .001 inches. For example, the out-of-plane distortion at 10 inches TRANSVERSE and 2 inches LONGITUDE, in the matrix labeled "DISTORTION MEASUREMENTS OF 3/16" PLATE AFTER WELDING" is -0.075 inches (i.e. 0.075 below the reference point). This point is designated D(6,2) as it is on the 6th line in the TRANSVERSE direction and the 2nd line in the LONGITUDE direction.

DISTORTION MEASUREMENTS OF 3/16" PLATE PRIOR TO START OF SECOND HEATING PASS

	TRANSVERSE																		
LONGITUDE	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
0	401		367	351	339		324		305	307	313		333		371	392	411		462
2				305.						257						350			
4	345			273			291			220			260			314			418
6				246						191						283			
8	291			220.			243			169			220			258			366
10				196						151.						238			
12	236	203.	183	174	176	185	195	171	148	135	137	146	181	195	205	221	242	270	315
14				158						120						205			
16	186			144			148			103			142			189			267
18				133						86						172			
20	145			127			106			75			107			153			222
22				119						72						135.			
24	125		112	100	92		80		83	75	66		76		100	122	130		179
26				47						48						86			
28	85			-30			54			32			66			70			146.
30				-43						20						61			
32	63			31			49			10.5			59			54			124
34				100						2						50.5			
36	50	52	83	105	104	85	49	16	3	0	12	31	54	47	43	46	53	70	111.
38				45						5						42			
40	51			-16			49			9			51			37.5			103.
42				-17						11						34			
44	56.5			14			51			23			51			34.5			104
46				50						41						41			
48	76		86	83	81		64		56	57	57		49		61	71.5			109
50				87.5						50						78			
52	91			90			81			46			70			80			115
54				91						48						84			
56	117			96			107			61			92			86			123
58				103						81						87			
60	146	126	115.	113	117	126	131	123	111	105	106	110	116	101	92	90	94	106	133
62				126						125						92			
64	180			137			159			135			141			98			146
66				151						142						109			
68	218			168.			187			149.			166			124			162
70				188						159.						144			
72	258		216.	206.	197		199		175	171	171		174		169	175	176.		181

DISTORTION OF 3/16" PLATE AFTER PANEL 5 WAS HEATED THE SECOND TIME

		TRANSVERSE																		
		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	381		346	330	317		301		281	283	289		309		347	367	387		437
	2				285						233						326.			
	4	327			253			267			196			236			290			393
	6				226						164						260			
	8	275			200			220			140.			197			235			340
	10				176						123						215			
	12	220	187	165	155	155	162.	172	145	120	106	108	122	158	172	183	199	218	245	289
	14				137						92						182			
	16	172			124			126			78			119			165			241
	18				113						66						148			
	20	132			107			84			58			83			128			196
	22				100						53.5						111			
	24	113		98	84	74		58		59	52.5	43		51		74	98	105		154
	26				33						48						62			
L	28	76			-44			35			43			42			48			121.
O	30				-46						34						40			
N	32	57			23			30			19			37			35			101
G	34				96						4						33			
I	36	47	50	81	103	100	75	32	10	2	0	10	21	34.5	30	28	31	37	51	90
T	38				42						12						29.5			
U	40	51			-18			36			25			33			25			83.5
D	42				-20						33						21			
E	44	60			12			42			42			37			21			86
	46				50						48						26			
	48	84		89	84	80		59		48	48	47		37		49	57.5	62		92
	50				88						45						64			
	52	101			92			78			43			60			67			99
	54				96						46						72			
	56	131			103			108			59			86			74			110
	58				113						80						77			
	60	165	143.	130	125	127	133	137	126	112	104.	105	109	114	97	85	82.5	85	96	121
	62				140						126						86			
	64	204			154			170			140			142			93			136
	66				171						148						106			
	68	247			191			202			159			171			122			155
	70				212						171						144			
	72	292		246	233	221		220		191	184.	182		181		172	176.	177		176

DISTORTION OF 3/16" PLATE AFTER PANELS 5, AND 6 WERE HEATED THE SECOND TIME

TRANSVERSE

		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	372		339	323	311		294		276	278	285		305		344	363	384.		436
	2				279						228						325			
	4	320			247			263			191			233			288			391
	6				220						159						257			
	8	269			195			215			137			194			232			338.
	10				171						119						213			
	12	215	182.	160	150	150	159	168	141	116	102	104	119	155	169	180	197	216	243	287
	14				133						88						181			
	16	169			120			122			75			115			166			239
	18				110						62						149			
	20	130			104			82			54.5			80			131			193
	22				98						51						112			
	24	113		96	82	72		57		57	50	41		48.5		71	95	102		151
	26				32						46.5						76.5			
L	28	76			-43			33			43			41			70			118
O	30				-55						33						65			
N	32	58			29			31			18			39			60			99
G	34				98						2						59			
I	36	48.5	51	83	105	103	78.5	35	11	1	-2	8	21	37	42	50	57	58	61	89
T	38				46						12						57			
U	40	53			-15			40			28			38			54			86
D	42				-16						37.5						51			
E	44	63			17			47			48			43			48			92
	46				55						55						45.5			
	48	88		94	90	86		66		56	56	55		46		57	66	72		103
	50				95.5						55						77			
	52	107			101			89			54			74			83			116
	54				104						58						90			
	56	137.			112.			120			73.5			103			94			131
	58				123						95						99			
	60	172.	151.	139	135.	138	146	151	141	127.	122	123	128	134	118	106.	105.	108	120	147.
	62				152						145						111			
	64	212.			166			186			160.			166			120			169
	66				183						170						136			
	68	256			204			220			182			198			154			192
	70				226.						194						178			
	72	305		259	248.	238		240		215	211	210		212		206	213	214		217

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 6, AND 2 WERE HEATED THE SECOND TIME

		TRANSVERSE																		
		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	365		331	316	303.		289.		270	272	280		305		346.	368	390		445
	2				273						240						327.			
	4	313			243			257			217			231			291			399
	6				217						194						262			
	8	263			192			210			173			192			237			345
	10				169						155						219			
	12	211	179	157	148	148	155	163	154	145	138	136	136	153	173	188	204	224	249	292
	14				131						124						189			
	16	166			119			117			110.			115			174			243
	18				110						95						157			
	20	130			104			78			80			80			137			197
	22				98						63						115			
	24	113		96	82	71		55		56	49	40		48		73	96	105		155
	26				31						46						77			
L	28	78			-45			33			43			42			71			121
O	30				-53						34						66			
N	32	62.5			25			33			18.5			39.5			62			102
G	34				101						3						61			
I	36	54	56	87	110	107	82	37	13	2.5	0	10	23.5	38.5	45	53	59	61.5	65	92
T	38				51						14.5						60			
U	40	60			-10			44			31			41			58			89
D	42				-10						41.5						55			
E	44	72			24			54			52.5			47			51			94
	46				63						60						49			
	48	99		104	99	94		72.5		61	61	60		50.5		61.5	70	75		105
	50				105						61						80.5			
	52	120			111			98			61			80			86			118
	54				115						65						93			
	56	151			124			129.			80			110			98			132
	58				135						103						102			
	60	188	166	153	148	151	157	162	151	137	130	131	135	140	124	112	109	112	123.	149
	62				165						154						114			
	64	228			180			198			169			173			124			170
	66				198						179						139			
	68	275			219			233			191			205			157			192
	70				242						205						180			
	72	321		276	265	253		252.		225	220	218		219		210.	215	216		217

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 6, 2, AND 8 WERE HEATED THE SECOND TIME

		TRANSVERSE																		
		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	371		336	321	308		293		272	274	281		305		347	367.	390		444
	2				277						242						327.			
	4	319			247			261			219			232			292			398
	6				221						194						262			
	8	266			196			212			175			193			238			244
	10				172						157						220			
	12	214	182	160	150.	150.	157	164	156	147	139	137	136.	155	174	188	205	224	250	293
	14				134						126						190			
	16	167			121			120			112			117			175			243
	18				111						97						158			
	20	130			105			79			81			82			138			198
	22				99						63.5						117			
	24	113		97	82	72		56		57	50	41		50		74	98	106		157
	26				31						47						78.5			
L	28	78			-44			34			44			43			73			125
O	30				-53						34.5						68			
N	32	61.5			25			33			18			41			64			106
G	34				102						2.5						63			
I	36	53	56	87.5	110	107	82	37	13	2	0	10	14	41	57	54.5	62	63.5	67	96.5
T	38				49						15						63			
U	40	59			-11			44			32			43			60			94
D	42				-12						43						57			
E	44	69			22.5			52			54			48			54			100
	46				61						61						52.5			
	48	95.5		101	96	92		71		61	61	61		52		64	74	79		111
	50				102.						79						86			
	52	116			108			97			91			81			92			124
	54				112						100						99			
	56	147			120			128			113.			111			104			139
	58				131						132						110			
	60	184	162	150	145	148	156	160	161	157	155	154	148	143	129	120	117	120	131	157
	62				162						175						123			
	64	225			178			197			187			176			133			179
	66				197						194						148			
	68	270			217.			232			202			208			164			202
	70				240						211						188.			
	72	312		273	262	251		253		227	222	222		224		217.	223.	225		228

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 6, 2, 8, AND 1 WERE HEATED THE SECOND TIME

TRANSVERSE

		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	365		329	313	301		287		268	270	278		303		345	366	389		444.
	2				291						238						326			
	4	313			277			253			215			230			291			399
	6				258						193						261			
	8	262			235			206			173			191			237			345
	10				209						155						218			
	12	209	196	192	186	180	171	159	153	145	139	136	135	153	172	186	203.	223	249	293
	14				167						126						189			
	16	163.			151			115			113			115			178			244
	18				135						97						158			
	20	127.			120			77			81			79			138			199
	22				103.						63						116			
	24	112		94	80	70		53		55	48	40		48		74	98	106		158
	26				28						45.5						79			
L	28	77			-48			32			42			42			73			126
O	30				-56						33						69			
N	32	61			26			31			17.5			41			65			107
G	34				101						2						64			
I	36	53	55	88	111	107.	82	36.5	12	2	0	10.5	25	41	48	56	63	65	69	98
T	38				49.5						15						64			
U	40	59			-11			44			32			44			61			96
D	42				-11						44						58			
E	44	71			23			53			55			50			56			102
	46				62						63						54			
	48	97.5		102	98	93		73		63	63	63		54		66	76	81		114
	50				104						82						88.5			
	52	117			110			98			94			84			95			128
	54				114						103						102			
	56	149			123			131			117			114			108			145
	58				134						136						114			
	60	187	165	152.	148	151.	159	164	165	161	157	158	153	147	133	123	121	124	135	162
	62				166						179						128			
	64	228			182			202			191			180			138			184
	66				201						199						152			
	68	274			222			237			206			214			172			207
	70				245						216						195			
	72	322		278	267	257		258		233	228	227		229		226	229	231		234

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 6, 2, 8, 1, AND 3 WERE HEATED THE SECOND TIME

TRANSVERSE

		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	367		332	316	303.		289.		270	273	281		306		347	369	393		448
	2				294						241						341.			
	4	315			279.			256			216			233			315			401
	6				260						198						289			
	8	244			237			210			172			193			265			346
	10				212.						154						246			
	12	211	198	193.	189	182	173	162.	154.	145	138	135	135	154	183	208	231	248	263	292
	14				170						126						215			
	16	165			153			117			113			116			199			244
	18				137						98						178.			
	20	130			123			80			82			80			153			200
	22				106						64						123.			
	24	114		97	82	71		54		56	49	40		49.5		73	97	106		159
	26				30						47						79			
L	28	79			-47			33			43			43			74			126
O	30				-56						34						70			
N	32	62			27			33			18			41			66			107
G	34				102						2						65			
I	36	54	56.5	88	111	109	83	37	14	2.5	0	11	25	41	48.5	56	64	66	70	98.5
T	38				50						15						64.5			
U	40	59			-10			45			33			44			62			96
D	42				-11						44						59			
E	44	71			23.5			54			56			50.5			57			102
	46				62						63						55			
	48	97		102	98	93.5		72.5		63	63	63		55		66	76	81		114
	50				104						81						88			
	52	116			109.			97			93			84			95			127
	54				113						102						102			
	56	149			122			130			116			114			107			142
	58				133						134						113			
	60	185	164	151	147	150	158	163	164	159	157.	156.	152	146	132	123	120.	123.	135	161
	62				164						177.						127			
	64	226			180			200			190			180			137			181
	66				199						197						152			
	68	272			219.			235			205			213			170			206
	70				243						214						194			
	72	319		276	265	255		256		230	226	225		227		222	228	230		233

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 6, 2, 8, 1, 3, AND 7 WERE HEATED THE SECOND TIME

TRANSVERSE

		0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
	0	368		331	325.	303		289		270	273	280		305		347	368	392		448
	2				293.						240						341			
	4	315			279			256			216			232			315			401
	6				260						193.						289			
	8	263			237			210			173			193			265			346
	10				212						154						247			
	12	211	198	193.	189	182	173	163	155	146	139	135.	135	155	183.	208	231	248	263	293
	14				170						126						215			
	16	165			153			118			113			116			199			244
	18				138						98.5						179			
	20	129			123			78			83			80			154			199
	22				106						64						124			
	24	114		97	81	71		56		56	50	41		50		73	98.5	107		157.
	26				30						47						80			
L	28	78.5			-46			34			44			44			74			128
O	30				-55						35						71			
N	32	63			26.5			34			19			43			67			108
G	34				102						3						66			
I	36	54	57	89	112	109	84	38	14	3	0	11	26	43	49	57	65	68	71	100
T	38				52						16						66			
U	40	60			-10			46			34			45			63			97
D	42				-10						45						60			
E	44	72			24			54			56			51			58			103
	46				63						64						56			
	48	98		103	98	94		72		63	63	63.5		55		67	76.5	84		115
	50				113						83						89.5			
	52	118			125			98			95			85			96			129
	54				131.						105						103			
	56	150			142			132			118			116			109			145
	58				154						137						115			
	60	187	174	170	168	168.	168.	164	165	162	159	158.	153	148	134	124	122.	125	136.	162.
	62				186						180						129			
	64	227			202			202			192			181			139			184
	66				218.						199.						154			
	68	274			236			237			207			215			173			209
	70				253						217						194			
	72	323		279	268	257		259		233	229	228		230		225	231	232		235

DISTORTION OF 3/16" PLATE AFTER PANELS 5, 6, 2, 8, 1, 3, 7, AND 9 WERE HEATED THE SECOND TIME

TRANSVERSE

		0	2	4	6	8	10	12	14	16	18
	0	368		331.	315	303		289		270	273
	2				294						240
	4	315			279			256			216
	6				260						193
	8	264			237			209			172
	10				212						154
	12	211	198	194	188.	182	173	162	155	146	138
	14				170						135
	16	166			153			118			112.
	18				138						98
	20	130			123			78			82
	22				106						64
	24	115		96.5	83	72		55		56	49
	26				29.5						46
L	28	79			-46			34			43
O	30				-54						34
N	32	63			27			33			28
G	34				103						2
I	36	55	57.5	90	112	110	84	38	13	2	0
T	38				52						15
U	40	61			-9			45			33
D	42				-9.5						44
E	44	73			25			55			56
	46				63.5						63
	48	102		104	100	94		74		63	64
	50				116						84
	52	121			122.			101			98
	54				134						108
	56	153			145			134			122
	58				157						139.
	60	191	178	174	172	172	171	168	169	165	163
	62				190						180
	64	232			205			205			192
	66				223						200
	68	278			241			241			207
	70				258						217
	72	327		283	272	262		263		234	229

		20	22	24	26	28	30	32	34	36
	0	281		305		357	368	392		448
	2						342			
	4			231			314			400
	6						289			
	8			192.			264			345
	10						246			
	12	135	134	153	183	208	230.	247	262	292
	14						215			
	16			117			198			244
	18						178			
	20			80			153			199
	22						123			
	24	40		49		73	97	105		157
	26						79			
L	28			43			74			126
O	30						70			
N	32			41			66			108
G	34						65.5			
I	36	10	25	41	48	57	64	67	71	98
T	38						64			
U	40			44			61			96
D	42						57			
E	44			50			54			102
	46						52			
	48	63		54		67	76	82		114
	50						96			
	52			85			113			128
	54						129			
	56			115			142			143
	58						153			
	60	161.	156	147	156	162	165	161	154	162
	62						171			
	64			181			181			184
	66						194			
	68			215			205			210
	70						215			
	72	229		231		225	231.	233		238